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STUDY OF THE AIR FLOW MEASUREMENT PARAMETER FOR INTERNAL COMBUSTION ENGINE TEST BENCHES

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Abstract: This work aims to implement a measurement system for the airflow of an EA211 1.0 MPI Volkswagen engine. Based on the theoretical basis of mass flow calculation, a system was implemented in the laboratory that allowed obtaining, through the difference in pressure and air velocity and using ways to calibrate the measuring nozzle, the discharge coefficient of the entire system. From these data, it was possible to obtain the theoretical and absolute values of the mass flow of air entering the engine. With these results, it was possible to conclude that any sensor that measures pressure or flow must, considering experimental errors, coincide with the mass flow value obtained through the implemented system.

Keywords: mass flow, measurement system, air flow, discharge coefficient.

INTRODUCTION

Based on the idea of replacing fossil fuels such as gasoline and diesel with renewable sources, the Biogás project seeks to operate a commercial engine fueled by Biomethane from biodigestion processes. Several mechanical and engine control changes are necessary for the operation of this type of engine, as the instrumentation and measurement of gaseous and mass flow are the targets of this project.

Thus, it is necessary to know the parameters of the engine, understand its correct operation, and calculate the measurement values correctly. With a very detailed knowledge, applying biogas and obtaining its mass flow rate is vital for the project to be presented in a way that explains its efficiency and performance.

For correct air flow calculations, it used devices such as a pulse damping box, calibrated orifice plate, instruments for measuring the differential pressure, and software for acquiring and recording the measured values. Based on the measured quantities, verifying the engine's operating parameters, and calculating its efficiency, fundamental indicators for converting the desired fuels were possible.

This work shows the air flow measurement system present in the engine test laboratory of Faculdade Gama, Universidade de Brasília, and its calibration to obtain the discharge coefficient. It was possible to calibrate the entire system in the laboratory using a pulse-dampening box, an object with known air mass flow connected to the box, and a differential manometer connected next to the orifice plate on the box. Thus, this system will be applied to the engine under study to obtain the actual mass air flow value and later compare it with the values presented by the flow sensors. The preliminary results refer to the discharge coefficient of the measuring nozzle and the orifice plate belonging to the damper box.

DEVELOPMENT

The fluid that runs through the system under study can be characterized as transient flow, as there are load losses throughout the system, in addition to the variation in the throttle opening, causing changes in the volume admitted to the engine. Its flow is pulsating, a compressible fluid because its volume is not constant when the pressure varies.

As the system has many load losses from the box, passing through the duct that connects the engine to the throttle valve, the propagated measurement error increases considerably. In this way, reducing the load loss in the system reduces the experimental error, bringing results closer to the theoretical ones.

The primary way to measure air mass flow is from restriction flow meters for internal laminar flows. There are three main ones: orifice plate, venturi, and convergent nozzle. The orifice plate was the only one used in this work.

Restriction flowmeters are based on the acceleration of a fluid stream through the metering nozzle. According to Fox *et al.*

(2014), the variation in fluid flow velocity causes a variation in its pressure, and this variation in pressure (Δp) can be measured with a differential manometer. After the fluid passes through the nozzle, it accelerates in the so-called recirculation zone and then decelerates to fill the entire duct.

According to Figure 1, separating a tube with a nozzle into two zones, zone 1 is located before the nozzle and zone 2 after the nozzle, where the fluid has maximum acceleration, is precisely where the recirculation zone is more significant than another zone. D_t is the diameter between the orifice plates. Applying the continuity and Bernoulli equations and making some considerations, such as permanent, incompressible flow, along a flowing line, without friction, uniform velocities, and equal heights, we obtain Eq. 1, which shows the mass flow (Moran and Shapiro, 2005).

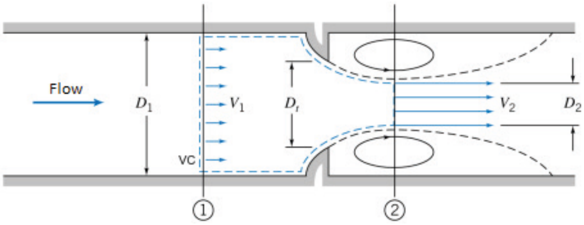

Figure 1. Internal flow through a generic nozzle. Adapted from Fox *et al.* (2014).

The following equation presents the calculation of the theoretical mass flow:

$$\dot{m}_{theoretical} = \frac{C_D A_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{2\rho(p_1 - p_2)} \qquad (1)$$

where ρ (kg/m³) is the specific mass, p (Pa) is the pressure, and A_1 and A_2 (m²) are the cross-sectional areas at sections 1 and 2.

The nozzle discharge coefficient (C_d) is the coefficient that includes in the calculations the deviation from the average discharge when applying Bernoulli. This coefficient is taken into account in measuring nozzles, and, for standardized nozzles, the C_d is already established (Brunetti, 2018). The C_d is the ratio of actual discharge to theoretical discharge, i.e., the mass flow rate at the discharge end of the nozzle to that of an ideal nozzle expanding an identical working fluid from the same initial conditions to the same output pressures.

ORIFICE PLATE

The orifice plate is a way to measure the flow rate. According to Fox *et al.* (2014), it is a thin plate between pipe flanges. This plate decreases the diameter of the flow, causing a difference in velocity. Figure 2 shows the orifice plate and the flow of fluid passing through it.

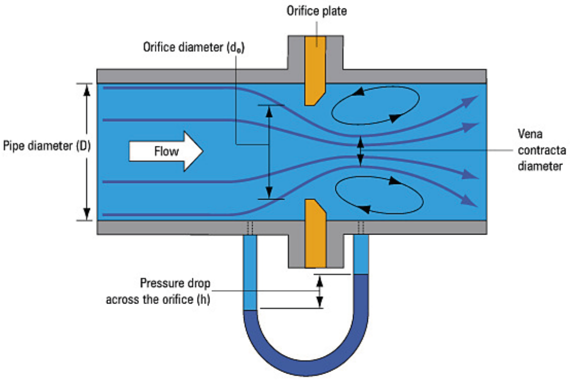

Figure 2. Orifice plate (Mohamed *et al.*, 2017)

According to Brunetti (2008), Eq. 2 and Eq. 3 show the formula for the flow of a fluid passing through an orifice plate.

$$Q = kA_0\sqrt{2g\frac{p_1}{\gamma}} \qquad (2)$$

$$k = \frac{C_D}{\sqrt{1 - C_C^2\left(\frac{D_0}{D_1}\right)^4}} \qquad (3)$$

Where:
Q: flow rate [m³/s];
γ: specific weight [N/m³];
g: acceleration due to gravity [m/s²];
k: dimensionless coefficient;
C_C: contraction coefficient [m/m];

$\frac{D_0}{D_1}$: : ratio of the diameters of an internal flow in a nozzle [m/m];

VENTURI

Still, according to Brunetti (2008), Venturi tubes are composed of a throat, convergent and divergent tube. Figure 3 shows that the Venturi tube is represented with a differential manometer. Eq. 4 shows its mathematical formula.

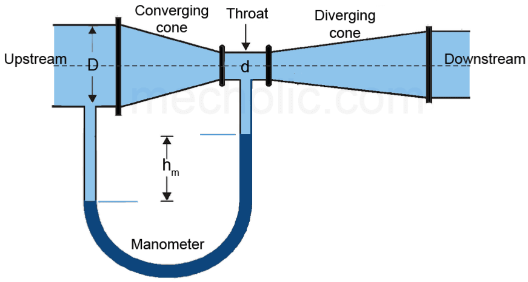

Figure 3. Venturi tube (Mecholic, 2020)

Following its equation:

$$Q = \frac{CA_2}{\sqrt{1-\left(\frac{D_2}{D_1}\right)^4}} \cdot \sqrt{2g\left(\frac{p_1-p_2}{\gamma}\right)} \qquad (4)$$

where C is Reynolds coefficient related to $\frac{D_0}{D_1}$: .

CONVERGING NOOZLE

The converging nozzle has the walls of the site with reduced diameter converge, forming a funnel. A flow detachment is included in it, which gives rise to a fluid region without translational movement. Eq. 5 brings the flow calculation.

$$Q = kA_2\sqrt{2g\left(\frac{p_1-p_2}{\gamma}\right)} \qquad (5)$$

Figure 4 shows its profile. P and T are initial pressure and temperature. P* and T* are final pressure and temperature.

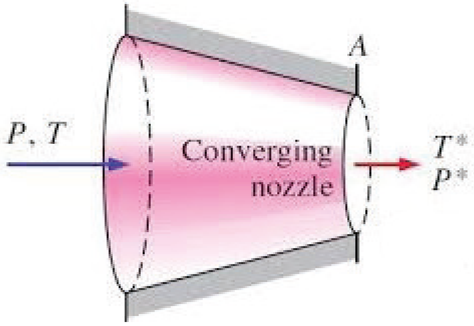

Figure 4. Convergent nozzle (Ratnam.Maddu et al., 2018)

METHODOLOGY

The mass air flow measurement system was installed in the laboratory. It has a pulse-dampening box (dimensions: 58 cm high x 66 cm wide x 66 cm deep), shown in Figure 5. At one of its ends are an orifice plate (diameter: 44.81±0.05cm) and a thin tube next to the plate, which connects to a differential manometer inside the laboratory. At the other end, a duct connects to the engine intake inside the laboratory.

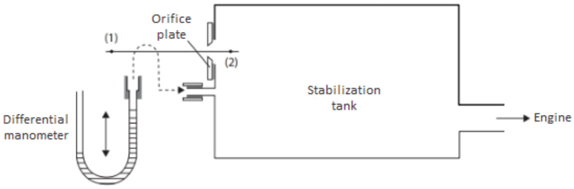

Figure 5. Schematic layout for measuring air consumption for the engine (Brunetti, 2018).

The schematic in Figure 6 shows how the entire system was connected.

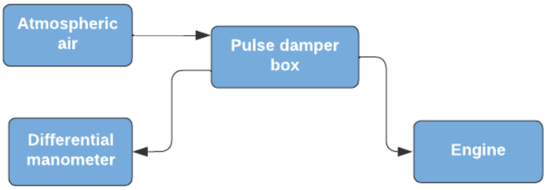

Figure 6. Airflow measurement schematic

As the objective is to discover the mass flow that enters the engine through this system, it was necessary to calibrate it. The calibration method was to replace the engine with a known airflow apparatus. The device used was a vacuum cleaner Universal Aspirator BT-VC 1250 S-220.

The vacuum cleaner airflow was obtained using an anemometer B-MAX (velocity error of 0.05 m/s and 0.05 °C) to measure the air velocity, a caliper Eccofer (error of 0.025 cm) for the vacuum tube diameter, the cross-sectional area equation, and the air density. When connecting it to the system duct and turning it on, the water that filled the manometer suffered a height difference, indicating pressure variation.

Also, measuring the diameter of the nozzle and the orifice plate, using the pressure difference and the pressure in the nozzle section, it was possible to use the equations 6 to 15 to obtain the mass flow of the aspirator, of the nozzle and the plate. With these flows, the discharge coefficient of the system was calculated, nozzle and plate coefficients.

$$v_t = \sqrt{2 \cdot \frac{p_m}{\rho_{air}}} \qquad (6)$$

$$v_{nozzle} = \sqrt{2 \cdot \frac{p_{nozzle}}{\rho_{air}}} \qquad (7)$$

$$A_n = \frac{\pi \cdot D_n^2}{4} \qquad (8)$$

$$A_t = \frac{\pi \cdot D_t^2}{4} \qquad (9)$$

$$A_v = \frac{\pi \cdot D_v^2}{4} \qquad (10)$$

$$\dot{m}_{air} = \rho_{air} \cdot v_{air} \cdot A_v \qquad (11)$$

$$\dot{m}_{air_t} = v_t \cdot \rho_{air} \cdot A_t \qquad (12)$$

$$\dot{m}_{air_n} = \mathrm{v}_{\mathrm{nozzle}} \cdot \rho_{air} \cdot A_n \qquad (13)$$

$$CD_{plate} = \frac{\dot{m}_{air_t}}{\dot{m}_{air}} \qquad (14)$$

$$CD_{nozzle} = \frac{\dot{m}_{air_n}}{\dot{m}_{air}} \qquad (15)$$

Being:

- p_{amb}: ambient pressure [kPa];
- T_{amb}: ambient temperature [°C];
- D_n: diameter in the nozzle section [m];
- D_t: diameter in orifice plate section [m];
- D_v: vacuum cleaner hose diameter [m];
- v_{air}: air velocity in the vacuum cleaner hose [m/s]
- p_m: pressure read on the column manometer [kPa]
- p_{nozzle}: pressure read on the digital manometer in the nozzle section [Pa]
- ρ_{air}: air density [kg/m^3]
- v_t: air velocity in the shock absorber tube [m/s]
- v_{nozzle}: air velocity in the nozzle [m/s]
- A_n: area in the nozzle section [m]
- A_t: area in orifice plate section [m]
- A_v: area in the vacuum cleaner section [m]
- m_{air} : mass flow of air in the vacuum cleaner [kg/s]
- m_{airt} : mass flow of air in the orifice plate [kg/s]
- m_{airn} : mass flow of air in the nozzle [kg/s]
- C_{Dplate} : discharge coefficient of the orifice plate [dimensionless]
- $C_{Dnoozle}$: nozzle discharge coefficient [dimensionless]

RESULTS

After the system calibration process, some results related to the equations described in the previous topic were obtained. Their values are shown in Table 1.

Variable	Value
T_{amb}	27 °C
p_m	101 kPa
ρ_{air}	1,2754 kg/m^3
p_{nozzle}	8 Pa
D_n	0,0889 m
D_t	0,0445 m
D_v	0,032 m
v_t	12,58 m/s
v_{nozzle}	3,542 m/s
v_{air}	41 m/s
A_n	6,21*10^{-3} m^2
A_t	1,556*10^{-3} m^2
A_v	8,04*10^{-4} m2
m_{air}	0,042 kg/s
m_{air_t}	0,025 kg/s
m_{air_n}	0,028 kg/s
CD_{plate}	0,595
CD_{nozzle}	0,667

Table 1. Equation variables for mass flow and discharge coefficients and their preliminary values

The results obtained were preliminary. Despite the measurements being made using experimental error, the error was not propagated because it is a preliminary measurement system analysis.

Of all the values in the table, the main one found was the discharge coefficient. This coefficient is essential as it allows to find the mass flow from it. Knowing its correct value, it is possible to assume that the system is calibrated. When using the Volkswagen EA211 1.0 MPI engine, the mass flow is calculated from the already established discharge coefficient.

By improving the acquired data, obtaining the transfer functions of the flow sensors, and validating the results with these calibrated sensors, it is possible to get a system that works not only for the study engine but that obtains the mass flow values for several bench engines.

CONCLUSION

After calibrating the system and obtaining the results of mass flows and discharge coefficients, it is possible to map the next steps of the work. As no more recent studies on the subject or works citing proposals similar to the one presented in this work, comparing methodology and results is not possible at first.

Preliminary values help in understanding what should be done for the next steps. These are: the inclusion of errors in the calculations; validation of calculated values, such as discharge coefficient, mass airflow, and transfer function of flow sensors; convergence of the values analyzed experimentally with the values presented by the ECU, acquired by the flow sensor; biofuel mass flow analysis in the engine; and validation of the system so that another bench engine can be tested and be able to measure its mass airflow parameters correctly.

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