

Description and Performance Analysis of a Flow Test Rig to Simulate Altitude Pressure Variation for Internal Combustion Engines Testing

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ABSTRACT

Calibration of internal combustion engines at different altitudes, above or below sea level, is important to improve engine performance and to reduce fuel consumption and emissions in these conditions. In this work, a flow test rig that reproduces altitude pressure variation is presented. The system stands out by its altitude range, compactness, portability and easy control. It is based on the use of turbomachinery to provide the target pressure to the engine intake and exhaust lines.

The core of the system is composed of a variable geometry turbine (VGT) with a waste-gate (WG) and a mechanical compressor. Given a set of turbomachinery systems, the operation pressure and the air mass flow are controlled by the speed of the mechanical compressor and the VGT and WG position. A simple modification in the installation setup makes possible to change the operating mode from vacuum to overpressure. So that simulating altitude increase or decrease with the same flow test rig components.

The installation concept has been validated experimentally based on a demonstrator. The experimental data are complemented with the analysis of computational results obtained from fluid-dynamic modeling. The results allow analyzing in detail the pressure and air mass flow operating range, the dependence on required subsystems characteristics, the potential for temperature regulation, the behavior under engine transient operation and the control strategies.

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INTRODUCTION

Due to the importance of having standard properties of the atmosphere at different altitudes, the International Civil Aviation Organization (ICAO) established the International Standard Atmosphere (ISA) [1]. ISA is an atmospheric model of how pressure, temperature, density and viscosity of the Earth's atmosphere change over a wide range of altitudes. It has been established to provide a common reference for temperature and pressure and consists on tables of values at different altitudes. According to ISA, the pressure and temperature variations within the troposphere, which is the lowest layer of Earth's atmosphere, are given by equations (1) and (2) respectively, as a function of the altitude. Figure 1 represents these pressure and temperature variations.

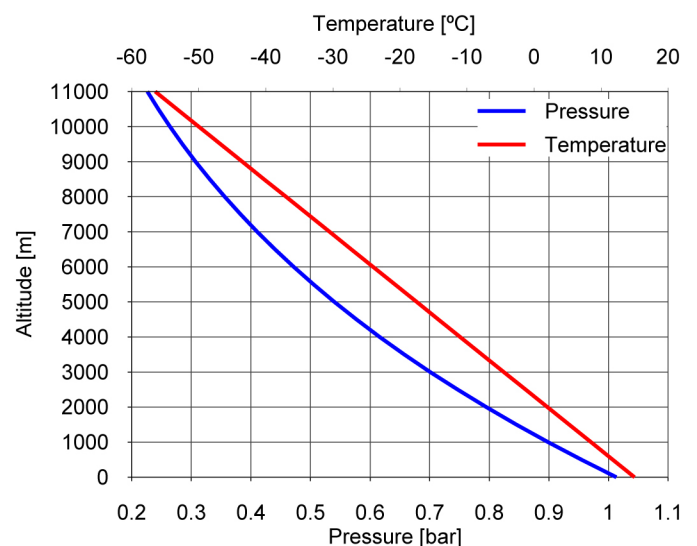


Figure 1. Altitude variation of pressure and temperature according to ISA.

$$p_h = p_{sl} \left(\frac{T_{sl} + h\lambda}{T_{sl}} \right)^{\frac{g_{sl}}{R_{sl}\lambda}} \quad (1)$$

$$T_h = T_{sl} + \lambda h \quad (2)$$

When engine performance change with altitude wants to be studied the important change in pressure is demanding its precise control both in the intake and the exhaust line of internal combustion engines (ICE) during testing and characterization in test cells. The temperature control at engine intake is also important but its variation is not only dependent on altitude but other constraints such location or season. Test campaigns performed to calibrate the engine control with altitude, cold start studies or repeatability of reference conditions in test campaigns that extend over time are other examples requiring pressure control. Depending on the test cell location, altitude simulation may require to decrease or increase the available atmospheric pressure.

In many cases, the difficulty is to control the pressure to simulate a higher altitude, that is, to obtain a constant and lower pressure than atmospheric pressure. However, in other cases it is also desirable to reproduce conditions of lower altitude, increasing the atmospheric pressure [2].

Due to these requirements, that modify the overall behavior of the engine [3, 4], its emissions [5, 6], and the behavior of its turbomachinery [7], many systems have been developed to simulate different altitude conditions in the air flow of the intake and the tailpipe of an engine. For example, Marchitelli et al. [8] presents an installation that can reproduce altitude conditions. This installation can change pressure of the atmospheric air by means of two roots compressors, one upstream of the engine connection and other downstream. Additionally an independent air conditioning unit for temperature and humidity control is installed at the inlet of the system. In vacuum mode, the compressor downstream the engine connection turns moved by an electric motor and the other compressor generates the pressure losses, operating like a valve. In overpressure mode, they exchange their functions.

Other similar system is presented by Simperl [9], which uses two valves and two volumetric compressors to control the pressure, one of them upstream and the other downstream of the engine connection. In this case, the independent air conditioning unit to control the temperature and humidity is installed between the first valve and the engine intake. The operation mode is similar to the system described in [8], but now the pressure losses are generated by the valves.

The main difference with the flow test rig that is presented in this paper is that in [8] and [9] a turbine is not used to generate vacuum, but an expansion in a valve or a compressor. It forces to use an air conditioning unit to reduce flow temperature in any case, increasing energy consumption and installation costs.

The installation presented in this paper has a small size due to the use of turbomachinery, allowing it to be moved from one test cell to another. It contrasts to the system proposed by Pircher et al. [10], which is a room-based solution, what makes it bigger, more expensive and unable to be moved. To generate vacuum or overpressure, this proposal considers a compressor and a valve, but not a turbine, and an air conditioning unit to control the temperature and the humidity, what involves the same energy increase as the solutions described in [8] and [9].

In the following sections, the operating principle of the altitude installation presented in this paper is explained, as well as the function of each element composing the system and how the vacuum or overpressure and the air mass flow through the installation can be controlled. Besides, the main performance results obtained, both from tests and fluid-dynamic modeling, are exposed covering performance without an engine coupled and then coupled to an engine in transient and steady conditions.

INSTALLATION OPERATION DESCRIPTION

Figure 2 shows schematically the main components of the flow test rig, which is described in detail in [11] and [12], for vacuum operation mode.

The installation can be divided into two parts: the inlet line, which covers from the installation inlet (element (1) in Figure 2) to the engine inlet pipe (12); and the exhaust line, which is defined from the engine outlet (15) to the installation outlet (23). Both lines are connected by the engine by-pass pipe (13). In vacuum mode, valve (25) is fully closed.

The working pressure and mass flow across the flow test rig are set by the mechanical compressor speed (20), the VGT position (4) and the WG position (5). The atmospheric air passes through the VGT where is expanded and cooled down from ambient conditions to the pressure of the altitude that is being simulated. The VGT power is dissipated in an independent turbocompressor (7). Alternatively, the WG valve can be managed in parallel. Basically, it allows increasing the mass flow rate and pressure for a given VGT opening and mechanical compressor speed but without effect on flow temperature. When both flows, the one from the VGT and the other from the WG, join, an intermediate temperature is obtained at engine intake. The combination of the settings with the mechanical compressor speed allows controlling pressure and mass flow but also provides a good margin for temperature control, as forwards explained in the following sections.

Downstream of these two elements, a cyclonic separator (9) is installed to separate the possible ice generated because of very low temperature. After that, a heat exchanger system (10) is placed to recover energy at VGT and WG outlet from the exhaust gases (from pipe 16) for intake air heating purpose.

Then, the air is aspirated by the engine intake (12) and the excess air is by-passed to the tailpipe of the installation and diluted with exhaust gas of the engine. This by-pass pipe (13) ensures engine operation with equal intake and exhaust pressure being the valve (14) is fully open.

This mixed exhaust air, which in its operation with an engine is at high temperature, passes through a cooler (18) to ensure the safe operation of the mechanical compressor (23). It additionally reduces the compressor power consumption. To avoid the effects of condensates formed when the exhaust gas is cooled down, what may damage compressor blades [13], another cyclonic separator (19) is installed just upstream of the mechanical compressor. The risk of condensates and its generation rate is depending mainly on the equivalence ratio, dilution ratio and the cooler outlet temperature. The mechanical compressor speed is controlled by means of the electric motor speed (21) with a variable-frequency drive. Finally, the exhaust gases are discharged to the atmosphere (23).

In overpressure mode (Figure 3), the position of the air filter (1) is changed as well as the connection of the intake and exhaust to the engine or element being tested. The position of valves (14) and (25) are also changed; valve (14) is closed and valve (25) opened, changing the location of the by-pass (dilution) of the installation. According to this scheme the air mass flow is firstly compressed in the mechanical compressor and driven to the engine intake. Finally, the exhaust gases are expanded in the VGT and WG.

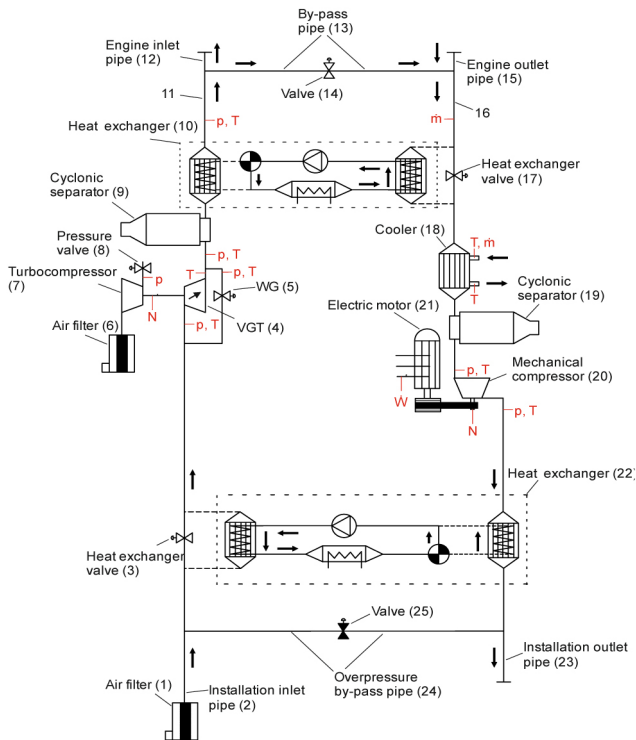


Figure 2. Scheme and main components of the flow test rig for altitude simulation in vacuum mode [12].

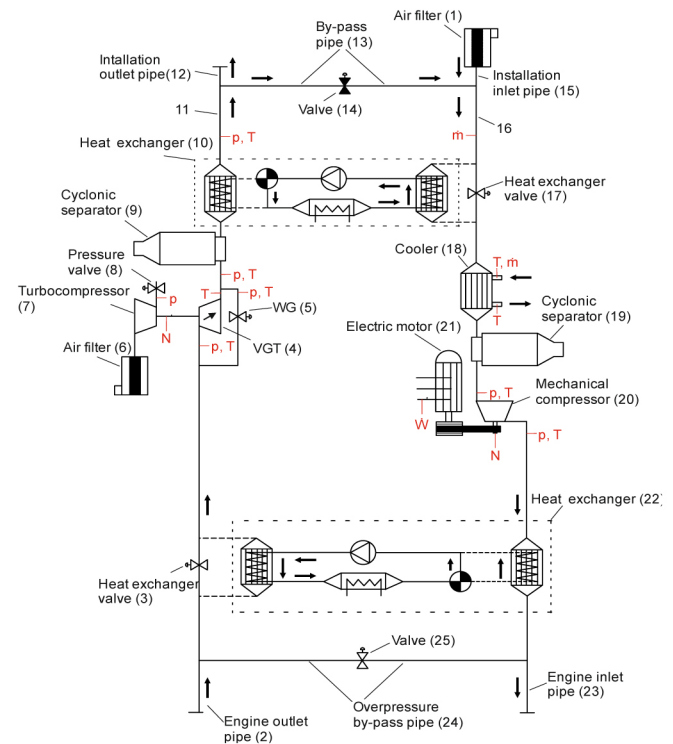


Figure 3. Scheme and main components of the flow test rig for altitude simulation in overpressure mode [12].

DISCUSSION OF THE RESULTS

In this section, the different performed tests and fluid-dynamic modeling and their conclusions are exposed.

Installation Performance in Vacuum Mode

The first step to assess the prototype flow test rig performance and analyze its capability for operation in vacuum mode covered a set of tests without coupling to any other system, i.e. by-passing all the flow from the intake to the exhaust of the installation.

Table 1 summarizes the technical specifications of the turbocharger and the mechanical compressor used in the demonstrator currently available. The characteristics of the turbomachinery are defining the range of operation of the installation. Therefore, they must be matched depending on the specific requirements.

In order to explore the mass flow and vacuum pressure range, its dependence and the available range for temperature control a parametric study was carried out. The speed of the mechanical compressor was swept for five combinations of VGT and WG opening, whose values are shown in the legend of Figure 4. The tested mechanical compressor speeds and its corresponding electric power are shown in Table 2.

Table 1. VGT, turbocompressor and mechanical compressor technical specifications.

VGT	
Model	Holset HY40V
Maximum reduced speed [rps/K ^{0.5}]	63.6
Maximum expansion ratio [t/t]	3.2
Maximum reduced mass flow [kg/s·K ^{0.5} /MPa]	60
Maximum inlet temperature [°C]	690
Inlet section [mm]	75 x 50.4
Outlet diameter [mm]	82
Turbocompressor	
Model	Holset HY40V
Maximum corrected speed [rpm]	130000
Maximum expansion ratio [t/t]	3.5
Maximum corrected flow [kg/s·K ^{0.5} /MPa]	114
Maximum outlet temperature [°C]	200
Inlet diameter [mm]	101.6
Outlet diameter [mm]	52
Mechanical compressor	
Model	C38-92
Maximum corrected speed [rpm]	90000
Maximum pressure ratio [-]	2.94
Maximum corrected flow [kg/s]	0.63
Inlet diameter [mm]	70
Outlet diameter [mm]	53

Table 2. Mechanical compressor speed and electric power consumption.

Mechanical compressor speed [rpm]	Electric power [kW]
9000	0,2
18000	0,5
27000	1,6
36000	3,0
41000	4,1
46000	5,2
55000	8,6
63000	12,3
71000	16,0
78000	22,0

Figure 4 shows the results for the described test. The x-axis on the top of the plot represents the pressure at the VGT outlet (pipe (11) in Figure 2) and the x-axis on the bottom its corresponding altitude according to ISA. As example, at 3000 m corresponds a pressure of 0.70 bar. The y-axis represents the air mass flow for each operation point.

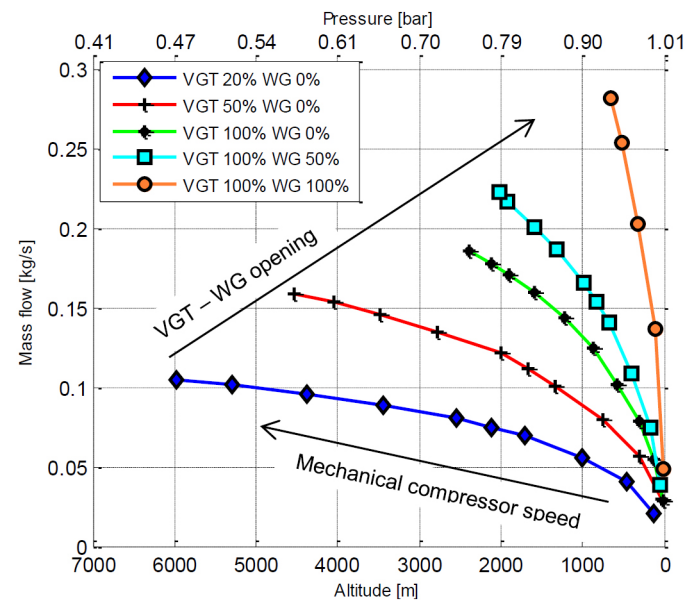


Figure 4. Installation performance in depression operation mode. For each VGT and WG position, different mechanical compressor speeds were tested.

Figure 4 shows that for the maximum mechanical compressor speed and the minimum VGT and WG opening (VGT 20% - WG 0%), the maximum altitude is emulated. It makes sense because the mechanical compressor is at its maximum power for that position and the free section through the VGT-WG is minimal, increasing expansion capability and therefore producing the highest vacuum and altitude. For this position, more than 0.1 kg/s air mass flow is obtained at 6000 meters of altitude (0.47 bar).

Similarly, the maximum air mass flow is obtained when the installation operates with the maximum mechanical compressor speed and maximum VGT and WG opening (VGT 100% - WG 100%). The reason is that with a bigger opening, increases the permeability of the VGT and WG and more air can pass through them at the expense of lower expansion ratio. The maximum air mass flow is obtained at 660 meters of altitude (0.915 bar). If the altitude is lower, the maximum air mass flow decreases according to the slope of the VGT 100% - WG 100% line. This slope is caused by the inlet line losses (pipe friction, elbows and valves).

Figure 5 represents the difference between the ISA temperature corresponding to every altitude and the VGT-WG outlet temperature (pipe (11) in Figure 2). The results point that ISA temperature is always lower than the temperature at the engine intake. It is caused mainly by the heat losses and by the VGT efficiency at different operation points.