Experimental investigation on the extreme cold start-up of an air compressor for electric heavy vehicles

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Gianluca Valenti[1], Stefano Murgia[2], Ida Costanzo[2], Antonino Ravidà[1], Giovanni Pio Piscopiello[1]

[1] Politecnico di Milano, Dipartimento di Energia, Milano, Italy
[2] Ing. Enea Mattei S.p.a., Vimodrone, Milano, Italy

E-mail: gianluca.valenti@polimi.it

Abstract. Engine-driven reciprocating air compressors are employed on fuel-powered heavy vehicles to actuate a number of auxiliary systems, like brakes and suspensions. Electrically-driven sliding-vane air compressors turn particularly suited for electric heavy vehicles. Unlike in fuel-powered vehicles, the compressor is not heated up in the case of electric mobility, a situation that may lead to potential issues in extreme cold weathers. This paper investigates experimentally the start-up of a sliding-vane air compressor designed specifically for electric heavy vehicles. The compressors, equipped with instruments, is positioned in a climatic chamber. During the tests, the chamber is set to a desired ambient temperature, 0, -10, -20, -30 °C or 20 °C taken as reference following ISO 1217, and the compressor is started-up when a steady-state initial condition is achieved. The delivery pressure is controlled at 10 bar(g) and all measurements are recorded until a temperature of 80 °C is reached in the air-lube oil separator. No issues are encountered during the tests, such as sudden damage due to improper lubrication. Moreover, the curves of the measured temperature within the air-lube oil separator show similar trends but higher initial plateaus and lower slopes at lower ambient temperatures resulting into lower oil flow rates, higher energy spent for heating up the system as well as higher warm-up times, from 15 minutes at 20 °C up to 69 minutes at -30 °C.

1. Introduction

Compressed air plays a key role in the heavy transportation sector, both on road and railways, for the actuation of bakes, doors, and suspensions. For the purpose of braking, compressed air systems require an accurate design that takes into account several factors, like volume flow rate, input power, noise, vibration and ambient condition, in order to guarantee a very high reliability [1].

In the case of rail applications, a modern braking system is based on the classic fail-safe Westinghouse concept that uses a reduction of the air pressure in the train line by way of a triple valve to apply the brakes [2]. Typically, compressed air is produced by electric-driven rotary compressors, like particularly sliding-vane compressors. In the case of heavy road applications, such as trucks and buses, today compressed air is produced commonly by engine-driven reciprocating compressors because these vehicles are powered commonly by diesel engines. However, in the scenario of the soon electric mobility, electric-driven sliding-vane air compressors turn to be particularly well suited for those vehicles, as for the trains, thanks to their low rotational speed, compact design, small weight, high efficiency, minimal vibration and modest noise compared to the reciprocating technology.

Engine-driven reciprocating compressors are heated up by the diesel engine and, hence, their start-up in extreme cold weathers does not lead to possible critical conditions because it is rapid. In contrast, electric-driven compressors are not heated up by the engine in the case of the electric mobility, a situation that could originate issues, such as the improper lubrication over long warm-up times due to the much higher viscosity of the oil at much lower temperatures than the steady-state operating temperature. The improper lubrication could lead to sudden damages as well as to slow wear. This paper presents the first stage of an experimental campaign dedicated to the start-up in extreme cold conditions of a sliding-vane air compressor designed specifically for electric heavy vehicles. The compressors is equipped with temperature sensors and pressure transducers; it is positioned inside a climatic chamber that controls both ambient temperature and humidity of the internal compartment; and it is started-up from different cold temperatures (0, -10, -20, and -30 °C). The goal of this first stage is observing the transient behavior of the compressor and measuring its warm-up time from each cold temperature. The warm-up time is a parameter of great importance because it is the time span during which part of the energy is spent to heat up the system and not to compress air. Consequently, it is the time span during which the performances are expected to be appreciably lower than at steady-state operating conditions. To the knowledge of the authors, the investigation of an electric-driven compressor inside a climatic chamber is novel in the open literature.

2. Experimental setup

The air compressor designed specifically for electric heavy vehicles here tested is a package comprising:

- a conventional filter for the air suction;
- a compression assembly with a 2.2 kW and 1500 rpm electric motor and a sliding-vane compressor;
- a separator assembly with a newly-designed air-lube oil separator and a coalescence filter;
- a conventional lube oil-cooling water heat exchanger.

The sliding-vane compressor is equipped with the novel lube oil injection system that employs both plain orifices and pressure-swirl nozzles to assure a proper lubrication of the compressor as well as an effective cooling of the air in the closed chamber during compression by way of the atomized oil. This injection system has been proved to reduce appreciably the compression power by Valenti *et al*. [3].

The compressed air-lube oil separator is designed with inertial principles to recover mechanically over 99% of the lube oil from the compressed air stream; the separator acts also as lube oil tank. The remaining oil is recovered by a following coalescence filter. The separator is designed also to operate with an inclination up to 20° in all directions.

The tested air compressor is equipped with six temperature sensors and two internal pressure transducers. Then, it is positioned inside a climatic chamber, model Discovery DY1200 by Angelantoni Test Technologies, capable of controlling temperatures from -40°C to 180°C and relative humidity from 10% to 98% in either constant conditions or along predefined cycles, as illustrated by Figure 1, left. In particular, one temperature sensor is immerged into the oil inside the air-lube oil separator close to the oil outlet; this temperature, as explained later, is taken as a primary measurement in this work.

The delivered air by the compressor is processed in a measuring and controlling rig. This rig comprises a manual regulation valve, two condensate separators to protect the following instruments, a pressure transducer connected to an automatic regulation valve, a thermal mass flow meter and, ultimately, a silencer (Figure 1, right). Signals from the instruments are acquired by a National Instruments cDAQ unit. At last, the compressor is connected to a cooling water loop and to the electric grid. Figure 2 shows the schematic of the tested compressor and the measuring and controlling rig, while Table 1 reports the information about the adopted instrumentation.

Figure 1. Left: the tested sliding-vane air compressor position inside the climatic chamber. Right: rig to measure and control the delivery pressure as well as to measure the mass flow rate.

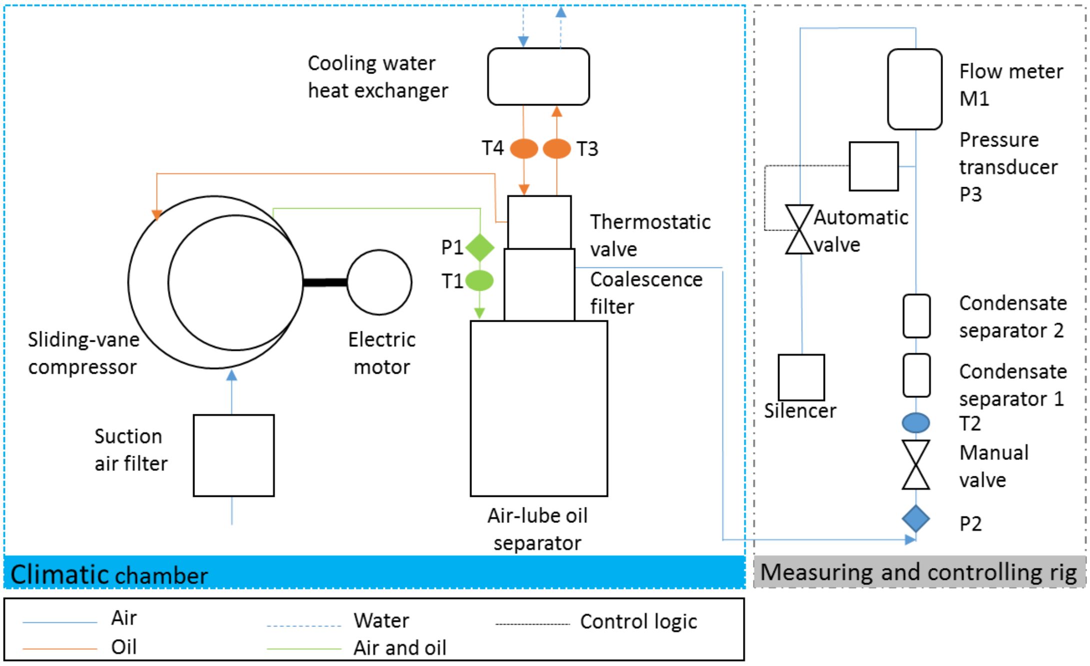

Figure 2. Schematic of the tested compressor in the climatic chamber and of the measuring and controlling rig.

Table 1. Instrumentation on the tested compressor and on the measuring and controlling rig (FS stands for full scale and RV for read value).

Quantity	Instrument	Manufacturer and model	Uncertainty	Unit
Temperature (T1 to T4)	T-type thermocouple	Tersid	0.5	°C
Relative pressure (P1 and P2)	Transducer	Remag PR1100	1% (FS)	bar (gauge)
Relative pressure (P3)	Transducer and valve	Bronkhorst High-Tech EL-PRESS P502C, F-002 AI	0.5% (FS)	bar (gauge)
Mass flow rate (M1)	Thermal meter	Bronkhorst High-Tech IN-FLOW F-113AI	0.5% (RV) + 0.1% (FS)	liter/s (normal)

The experimental campaign aims at observing the transient behavior of the compressor from the start-up at an extreme cold temperature and measuring its warm-up time. The considered ambient temperatures are 0, -10, -20, and -30 °C; in addition, the temperature of 20 °C is take as reference following ISO 1217. The start-up from each ambient temperature is repeated over three tests to verify visually the repeatability. The sequence of all tests for all temperatures are executed randomly to avoid systematic errors. The warm-up time is defined as the time the temperature of the air-lube oil separator needs to reach 80 °C. The value of 80 °C is chosen considering that the cooling water on electric heavy vehicles is typically available at about this temperature, which is lower than on diesel-engine vehicles because a traction electric motor must operate at a lower temperature than a diesel engine.

For a single test of a considered temperature, the experimental procedure includes the following steps:

- set the climatic chamber at a desired temperature;
- monitor the temperature in the air-lube oil separator till it reaches the desired temperature (it may take several hours);
- after at least one hour the separator temperate is at the desired value, start the compressor (without opening the cooling water circuit) and record the measures every 1 second;
- immediately set the delivery pressure at 10 bar(g);
- when the separator temperature reaches 85 °C, turn off the compressor.

3. Results and discussions

Figure 3 and Figure 4 illustrate the three-time repeated measures of the separator temperature, indicated with T1 in Figure 1, as a function of time till the temperature of 80 °C for each ambient temperature. The curves at 20 and 0 °C overlap very closely, while those at -10, -20, and -30 °C show differences that are anyhow minor. Therefore, all the recorded measures prove to be repeatable.

In its turn, Figure 5 compares the averaged measures of the separator temperature for each ambient temperature. All curves have an initial plateau lasting less than 1 minute for the ambient temperatures of 20 and 0 °C and more than 1 minute, but anyhow less than 4, for all others. The plateau width indicates the time the cold oil within the separator needs to be displaced by the warmer oil coming from the compressor. Consequently, it is an indirect indication of the oil flow rate through the compressor. As a result, the oil flow rate at the start-up from -30 °C is about one third of that from 20 °C. The cause of the lower rate is the higher viscosity of the oil at the lower temperatures.

Moreover, all curves of Figure 5 show an oscillating behavior around the separator temperature of 70 °C at which the thermostatic valve of the compressor opens. This valve lets the lube oil flow to the cooling water heat exchanger only above the threshold of 70 °C, indeed, to allow for a faster start-up. On top of this, all curves have the same trend but slightly different slopes. These slopes turn flatter for the lower ambient temperatures, leading to higher and higher warm-up times. The cause of the lower slopes at lower temperature is the higher thermal dissipation in colder conditions, leading to higher energy consumptions for heating up the system and, likely, lower performances.

Ultimately, Table 2 summarizes the warm-up times, ranging between 15 minutes for the ambient temperature of 20 °C and 69 minutes for -30 °C.

Table 2. Measured warm-up times for the considered ambient temperatures. The value in parentheses indicates the variation with respect to the reference ambient temperature of 20 °C following ISO 1217.

Ambient temperature (°C)	Warm-up time (minutes)	
	Value	Variation
20	14.86	reference
0	23.81	+60.2%
-10	32.64	+120%
-20	41.51	+179%
-30	68.99	+364%

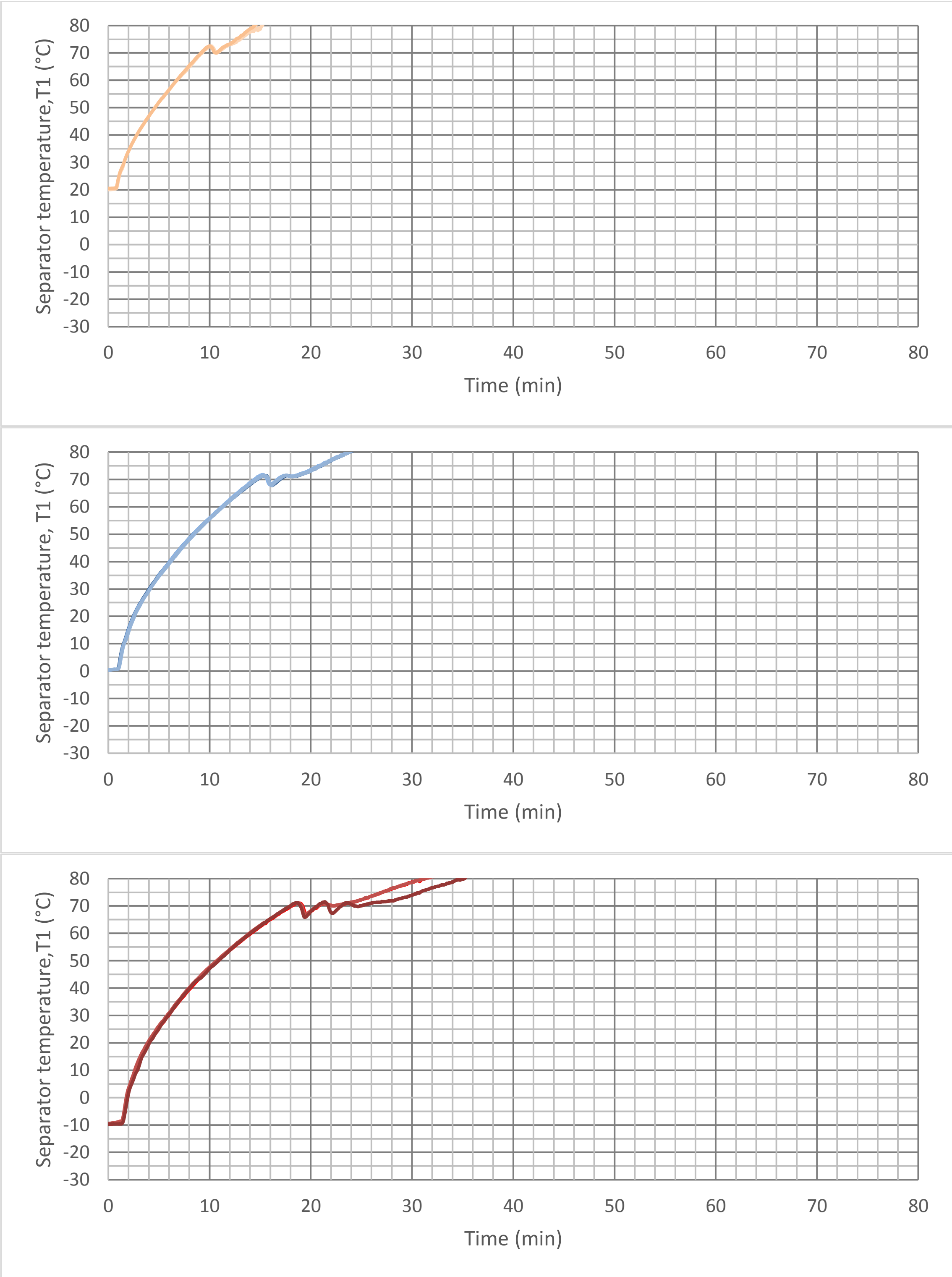

Figure 3. Repeated measures of the separator temperature as a function of time for the start-up from the ambient temperature of 20, 0, and -10 °C.

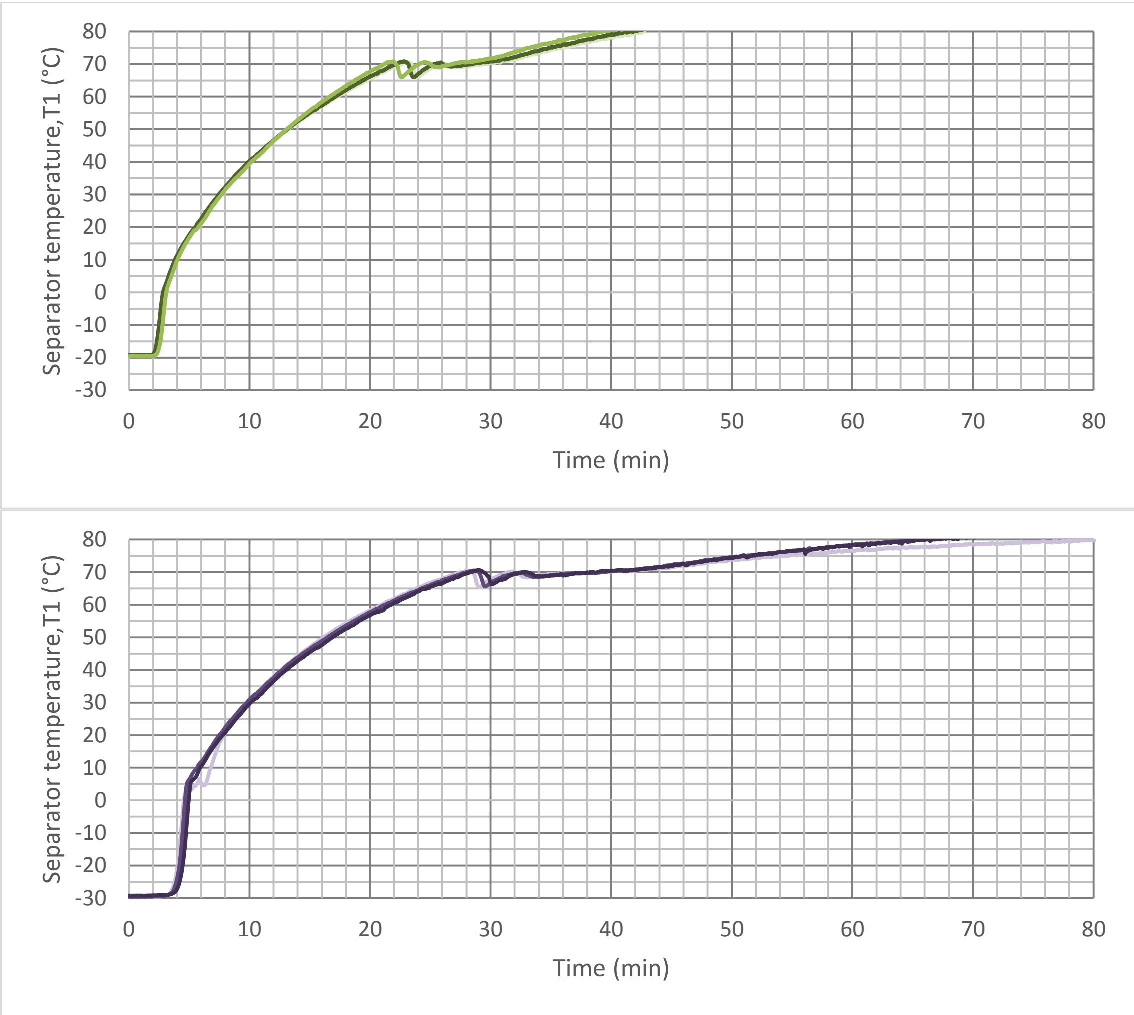

Figure 4. Repeated measures of the separator temperature as a function of time for the start-up from the ambient temperature of -20 and -30 °C.

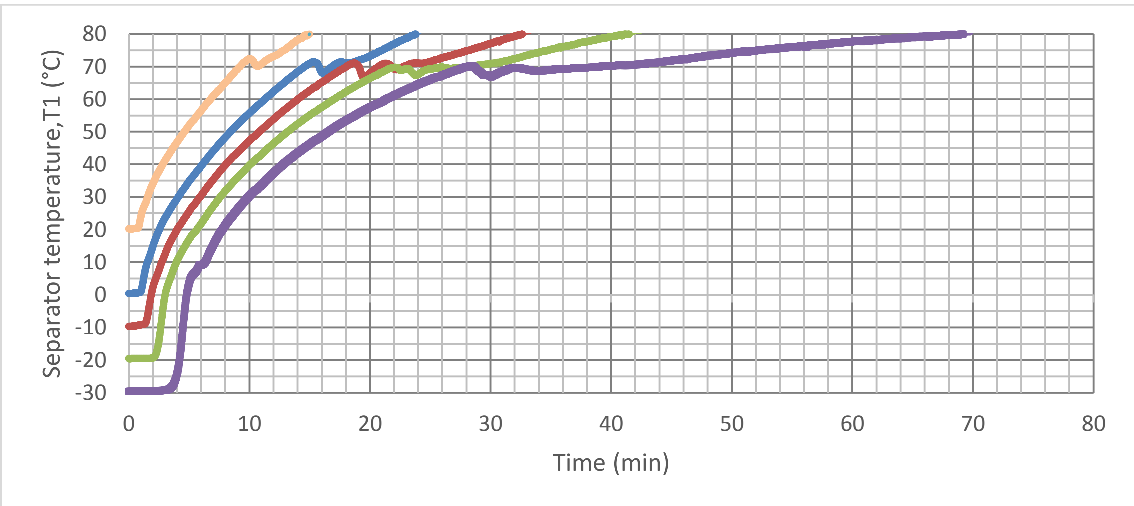

Figure 5. Averaged measures of the separator temperature as function of time for the start-up from the ambient temperature of 0, -10, -20, and -30 °C as well as 20 °C taken as reference.

4. Conclusions

This work presents the first stage of an experimental investigation of the start-up in extreme cold conditions of a sliding-vane air compressor designed specifically for electric heavy vehicles. The compressors is positioned inside a climatic chamber and started up from steady-state initial conditions at the temperatures of either -10, -20, -30°C as well as at the temperature of 20 °C taken as reference following ISO 1217. The temperature of the oil inside the air-lube oil separator is taken as indicator of the warm-up time. This work draws the following conclusions about the transient behavior.

- The compressor starts up from all extreme cold conditions in similar and repeatable manners and, in particular, without any issues, such as improper lubrication leading to sudden damages.
- All curves of the temperature within the air-lube oil separator show similar trends with differences in the width of the initial plateau and in the slopes after the plateaus.
- Larger initial plateaus at lower temperature indicate lower oil flow rates due to the higher oil viscosity. The start-up at -30 °C is characterized by about a third of the oil flow rate than at 20 °C. This lower flow rate is anyhow considered still sufficient to operate safely avoiding sudden damages as well as slow wear.
- The lower slopes at lower temperatures are due to the higher thermal dissipation in colder conditions. The lower slopes results into higher warm-up times at lower ambient temperatures.
- The warm-up time at the reference temperature is relatively short, with 15 minutes, but it can be quite long at -30 °C, with 69 minutes.
- Higher warm-up times indicates higher energy spent to heat up the system instead of compressing air and, likely, in lower compressor performances.

The second stage of the experimental campaign will focus on equipping the rig with the instruments for measuring the electric power consumption and the delivered air mass flow rate continuously during the warm-up time in order to evaluate the compressor performances as a function of time for the different ambient temperatures.

Acknowledgements

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References

[1] Schumann SP 2008 Air Compressor Systems for Passenger Rail Applications *Int. Comp. Eng. Conf. (Purdue, IN, U.S.A)*

[2] Di Stefano L 2008 Analisi dinamica di treni merci lunghi equipaggiati da un innovativo sistema frenante *MSc thesis at Università degli Studi di Roma Tor Vergata*

[3] Valenti G, Murgia S, Contaldi A and Valenti A 2014 Experimental evidence of the thermal effect of lubricating oil sprayed in sliding-vane air compressors *Case Studies Th. Eng.* **4** 113-117 doi:10.1016/j.csite.2014.08.001