Experimental study of the use of metal bellows as an Ericsson Engine Expansion Chamber

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Abstract:

In this paper, we present the results of experiments carried out as part of a phased approach of an external combustion engine developed by Assystem. The aim of this engine is to work with either an isothermal or an adiabatic process in the expansion chamber enabling the engine to operate following Ericsson or Brayton cycle respectively. To ensure such flexibility, the studied engine uses a welded metal bellows based technology. This solution allows a more efficient control of the thermal exchanges as well as the overcoming of the technological issues associated with classical engines such as the loss of working fluid or its contamination by lubricant and also the piston lubrication at high temperature. An experimental test bench has been designed to characterize the expansion chamber behaviour. The engine is instrumented to record pressures, temperatures in different locations of the system and also the piston displacement. After describing the principle of the engine and its operating cycle, the first experimental results of the expansion chamber behaviour are presented.

Keywords:

Ericsson; Brayton; Externally heated; Valve air engine; Caloric; Bellows.

1. Introduction

The present world is facing to a challenge of providing a sustainable development with an increasing of the worldwide energy needs whereas the global resources in fossil energies are diminishing [1]. To meet that expectation, housing seems the main object for efficient actions and most of all, the first field for energetic savings, *buildings are responsible for approximately 40% of the total world annual energy consumption* [2]. Assystem, an international company of engineering and innovation consultancy, has made the energy self-sufficient building one of its priority and the IndEHo[1] project is part of this policy. The IndEHo team is actually working on an external combustion engine (EC engine), also named externally heated valve engine (EHVE) [3], mainly based on the Ericsson cycle. Such family of engines, that includes the Stirling engine, was created in the 19th century but really used since the middle of the 20th century. Nowadays, they can have majors improvements thanks to advanced technologies [4] and materials [5]. Our version of the "Ericsson" EC engine is a part of

[1] IndEHo stands for **Ind**ependent **E**nergy **Ho**me

these improvements and has been patented [6]. As for all EC heat engines, some non-conventional heats sources can be used, such as solar [7], biomass or any thermal losses of some manufacturing process[8]. Since 2012, research works are conducted through a collaboration between the public research institute FEMTO-ST and the ASSYSTEM company. Its objectives are the validation and improvement of the thermodynamic model of this new EC engine, through a set of tests done by different versions of an experimental engine. The present paper takes interest on the sole expansion chamber behaviour (presently a Brayton one).

2. A newly designed external heat engine

In this part, we will first start with a generic description of the engine working principle, who can be based on the Joule-Brayton cycle or on the Ericsson cycle. In a second time, we will present the engine concept as part of inside the IndEHo project and how to make sure that last one of these cycles works at different nominal modes. One advantage of the Ericsson engine is it conception by modules " *It means that each part of the engine can be studied and optimized separately before being inserted in the whole engine"*[9], that was the reason why a step- by-step development of the experimental engine was admitted as the most powerful, fastest and safest way to do. One of the indirect consequences of this method is the uncoupling of the results. The studies of major evolutions of temperatures, with come from additional sources of heat, can only be achieved at the end of the development.

2.1 Operating principle

The operating cycle of the machine is described in order to point out its different functioning modes.

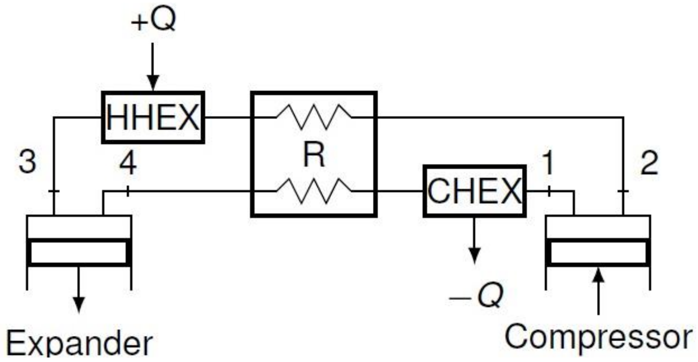

Fig. 1. Schematic representation of a metallic bellows based external heat engine

A vacuum is created when the moving part of the compressor (Fig. 1) moves down. It allows the working fluid [2] to enter the chamber through the opening of the suction valve (located next to point 1 of Fig. 1).

When this mobile part reaches its bottom dead centre, the suction valve (1) closes, that marks the end of the induction stroke. During the mobile part's ascent, compression stroke, the fluid is compressed until the discharge valve (2) opens, allowing the fluid to exit at higher pressure. The fluid flow is then heated throughout two heat exchangers. First, it passes through an economiser, on other words as a heat recovery exchanger (R), that preheat the gas flow before entering in a "hot" heat exchanger (HHEX). Now heated and pressurized, the gas flow is ready to be introduced into the expansion chamber throughout an intake valve located in (3).

The injection of the gas into the expander occurs when its mobile part is at its top dead centre. When enough gas has been introduced, the intake valve (3) closes. The injected fluid is then expanded and at the same time pushes the mobile part of the bellows until its bottom dead centre. This constitutes

[2] Working fluid can be air in an open cycle, any other type of gas in closed cycle.

the power stroke. That step can be controlled by either the displacement of the mobile part[3] or the pressure within the expansion chamber depending on the chosen control parameter. The sequence of opening/closing valves, the load and the pressure before and after the expansion chamber, determine the operating point of the engine and thus its power and its efficiency. Obviously, any mechanical load, as a generator, can be connected to the mobile part to generate power. The return[4] of the mobile part expelling the gas out of the expansion chamber through the exhaust valve (4), constitutes the exhaust stroke.

Before being once again aspirated into the compression chamber, the gas passes through a counter-flow the economizer (R) and then through a cold heat exchanger (CHEX).

It has to be noted that, if in the presented configuration, the compression chamber is not cooled and the expansion chamber is not heated, the working theoretical cycle is the Joule-Brayton, as in the Ericsson M1833 engine [9]. In the other case, if compression and expansion are done with some thermal exchanges, as in M1851[5] Ericsson engine[10][11], the working cycle is Ericsson one.

2.2 Description of IndEHo external heat engine

The engine which is investigated in term of the IndEHo project uses some welded metallic bellows instead of a conventional reciprocating device with pistons. The bellows are used as compressor and expander chamber as seen on Fig. 2.

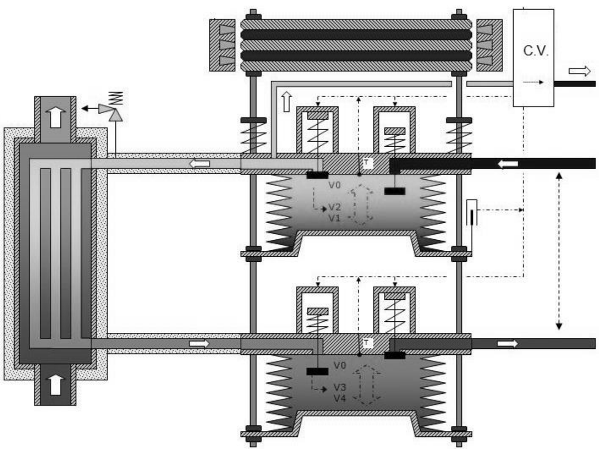

Fig. 2. Metallic bellows based external heat engine developed for the IndEHo project

Main difference resulting from the use of bellows' chamber as compressor and expander is that the valves[6] control internal volume variations. That process allows a flexible and accurate control without any mechanical system to lead the valves such as those used in other camshaft's engines [3] [9].

For a non-cooled compression chamber and a non-heated expansion chamber, the target cycle is the Brayton one with compression and expansion evolutions being ideally adiabatic [9]. Regarding to Fig. 2 it means that no additional exchanger is needed.

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[3] In case of crankshaft, displacement can be controlled by angular variations. In case of full linear device or free piston, displacement can be only controlled by linear variations (absolute values could be a better way to help to compare the angular controlled device)

[4] The return can be only realistic if a kinetic or potential energy was stocked in a device for this purpose, for example springs or inertial flywheel. Note that the engine conception implies a synchronous motion of both mobile parts.

[5] M1851 engine, produces 2kW to 3kW with an efficiency of 2.45 % at 30 to 50 rpm and 1.4 to 1.65 bar of pressure. Compressor's air is aspirated at 85.5°C and pulled out at 146.4°C, expander's air comes at 244°C and goes out at 311.4°C, the heater's temperature is 343°C. Compressor diameter is 1240 mm and expander diameter is 1504 mm with same stroke of 230 mm.

[6] With intake and exhaust valves driven by a pneumatic actuator leaded by solenoid valves. The variant of the engine done by step-by-step approach, uses directly the pneumatics actuators and solenoid valves, as the intake and exhaust valves.

For a cooled compression chamber and a heated expansion chamber, the aim is to get the Ericsson cycle. Compression and expansion evolutions are expected [12] to be quite isothermal. It implies the insertion of a heat exchanger in the compression and expansion chambers. The use of bellows ensures a better heat exchange control but also enables to avoid all the technological issues associated with classical reciprocating engines. The major problems are the piston lubricating oil at high temperature and the loss or pollution of the working fluid.

Another advantage of using a free stroke of bellows, is the opportunity of controlling the cycle according to the pressure within the expansion chamber or its linear displacement. Even if compressor [13] or ancient basic pump [14] based on such bellows system exists, when applied to engine, this approach seems to be still at its prototypical phase by Kohler [15], Colgate [16] and O'Hare [17].

Furthermore, it can be noted note that the working gas does not follow a closed cycle like in the theoretical case described above, so the expansion chamber can be connected to any compression device.

Such configuration enables to investigate the expansion chamber, to improve the diagnostic system and to master the injection/exhaust leading program. The present paper mainly focuses on that stage of the engine investigation.

3. Characterization of the bellows behaviour.

3.1 Description of the expansion chamber test bench

As previously said, if the bellows expansion chamber "works" alone, that should imply an adiabatic process. In order to check assumptions about driving of controls in regards of working conditions, a test bench has been built taking into account the only expansion chamber (Fig. 3).

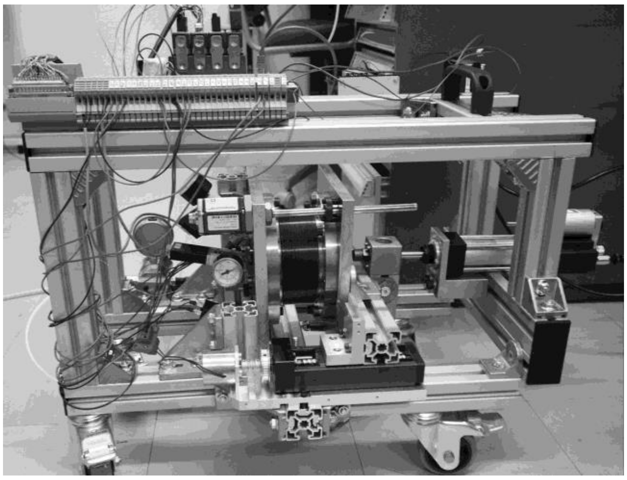

Fig. 3. Picture of the expansion chamber test bench

Based on the scheme of the test bench presented in Fig. 4, the facilities of the experimental device will be explained. First, it can be seen that as we initially were interested by the expansion side of the engine, so the economiser (R of Fig. 1) should be taken into account. The hot heat exchanger is then oversized to ensure its own job as well as that of the economiser (it is also called H on Fig 4).

The load of this configuration has two purposes: to ensure the connected power conversion load and to simulate the load due further connection with the compression chamber. By adjusting that load, the expansion of the bellows could be adjusted thus could modify the gas input volume. In this configuration we can consider that and it is the compression chamber that modifies the pressure ratio thus the engine power.

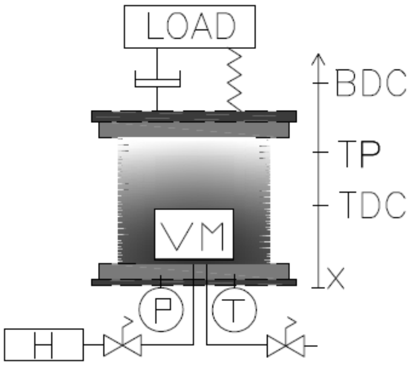

Fig. 4. Scheme of the expansion chamber test bench

Moreover, the expansion chamber has been designed so that a part VM (on Fig. 4) can be introduced within it in order to reduce the volume. The dead volume of the expansion chamber could be changed by translator movement of this piece. This functionality has been added to the last version of the test bench, because in other case the effective dead volume is bigger than the minimum one. The bellows has an incompressible dead volume of 0.2 litres i.e. a minimum height of 2.55 cm but depending on the working condition, the Top Dead Centre (TDC) position could be greater than those 2.55 cm implying a bigger dead volume. It means that the corresponding additional volume is a lost dead volume. The aim of this reducing system is to be able to reduce that useless volume and thus reduce the injected flow as well as the injection time and allows to reach higher frequency.

At last, the injection and exhaust of the gas within the chamber depends on the input and output valves opening. Those valves are electrically controlled depending on either the position of the bellows (volume) or the expansion chamber pressure. Both valves can be controlled by one parameter or by different at the same time, opening can be leaded by one parameter while closing is leaded by the others. It allows a wide range of valves opening cycle. Another solution is to program an opening valve cycle (i.e. programming the opening valves cycle with a chosen time sequence) and to record the matching working cycle. In order to prevent any damage of the test bench, safety parameters could be defined.

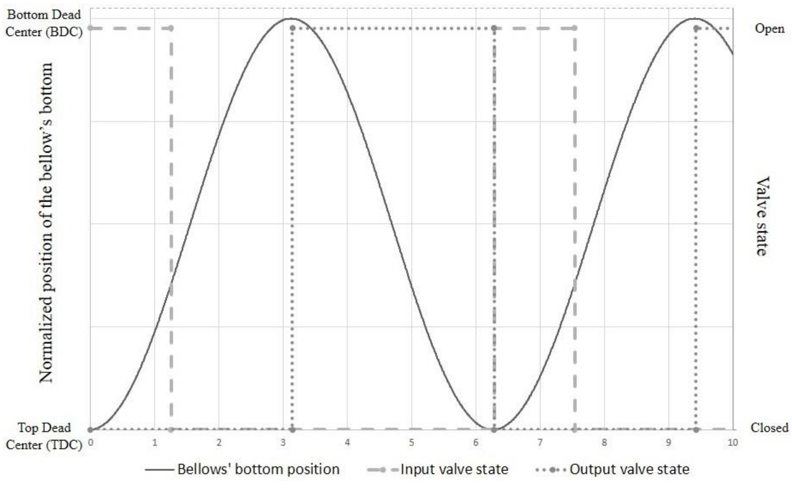

Fig. 5. Valves openings as a function of the bellows position

The opening of the intake valve occurs when the bellows expands from its Top Dead Centre (TDC) to a Transitional Position (TP), matching a versatile position variation of its end of injection. Intake valve is closed during the rest of the evolution. The exhaust valve opens when the bellows is at its Bottom Dead Centre (BDC) which means that the volume of the expansion chamber is maximal. It closes only when the expansion volume is lower corresponding to a bellows at its TDC. The behaviours of those valves are represented in Fig 5. It can be seen that the valves are never open simultaneously and that the exhaust valve remains open longer than the intake valve.

3.2 Description of the instruments used on the test bench

As the aim of this test bench is to characterize the thermodynamic evolution within the bellows, the expansion chamber is instrumented with thermocouples, pressure gauges and a displacement sensor allowing to record the evolution of those parameters during the different transformations generated (see Fig. 4). As the engine is supposed to work at medium frequency[7] (10 Hz and more), tests have been conducted on the micro-thermocouple sensors. The results presented in Fig. 6 show that 125 µm thermocouple results can be misleading. On the compression experiment (Fig. 6a), the 125 µm thermocouple seems to indicate that the compression is isothermal. That naturally identifies the sensor size choice for the experiments. The second experiment has been realised for a series of 1 Hz expansion-to-compression cycles (Fig. 6b) and also shows that smaller is thermocouple, faster is the response to fast variations [18]. For those reasons, they are best fitted for our investigations and thus, the test bench have been instrumented with them.

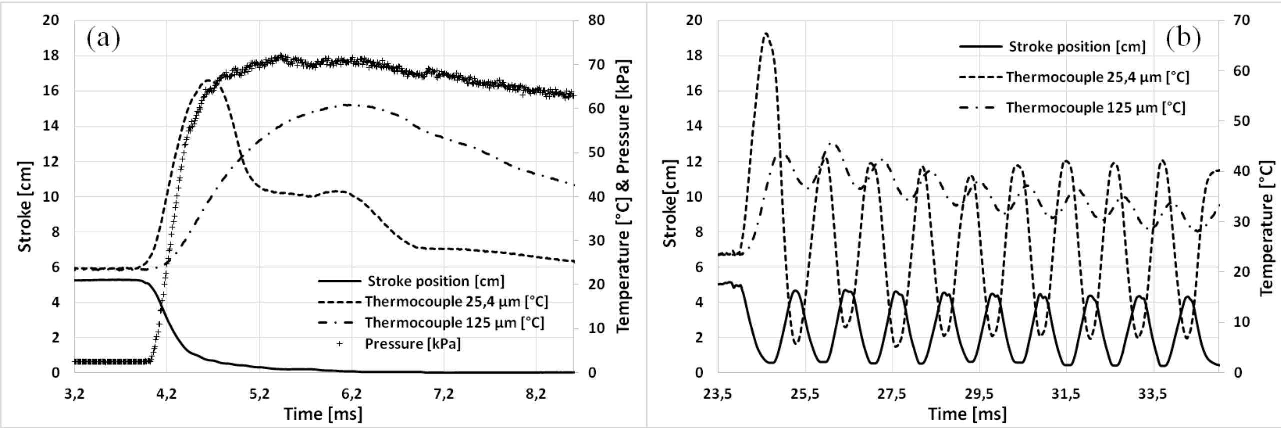

Fig. 6. Comparison of thermocouples response regarding their size for a single high compression (a) and for a high frequency expansion compression cycles (b) of the bellows chamber.

4. Experimental results of the expansion chamber

4.1 Description of the instruments used on the test bench

Experiments have been recording for the valves synchronization described in paragraph 3.1 with air at ambient temperature of approximately 300 K and a pressure of 5 bar before the intake electro-valves[8]. The dead volume reduction piece (VM) has not been used during this experiment and the initial condition in the expansion chamber are that of ambient air.

Table 1. Set points and relative positions

Set point	Relative position [cm]
Top Dead Center	4,8
Transitional position	4,9
Bottom Dead Center	5,3

Results of expansion chamber relative pressure and bellows mobile part are plotted versus time for a single cycle on Fig. 7.

[7] Identical tests were tried to reach an isothermal evolutions (n = 1), with a max variation of 5°C for the gas temperature, a polytropic factor of 1,161 is achieved for compression and factor of 1,116 for the expansion at a frequency of 0,006 Hz.

[8] This variant uses as the intake valve and exhaust valve the pneumatics actuators driven by solenoid valves.

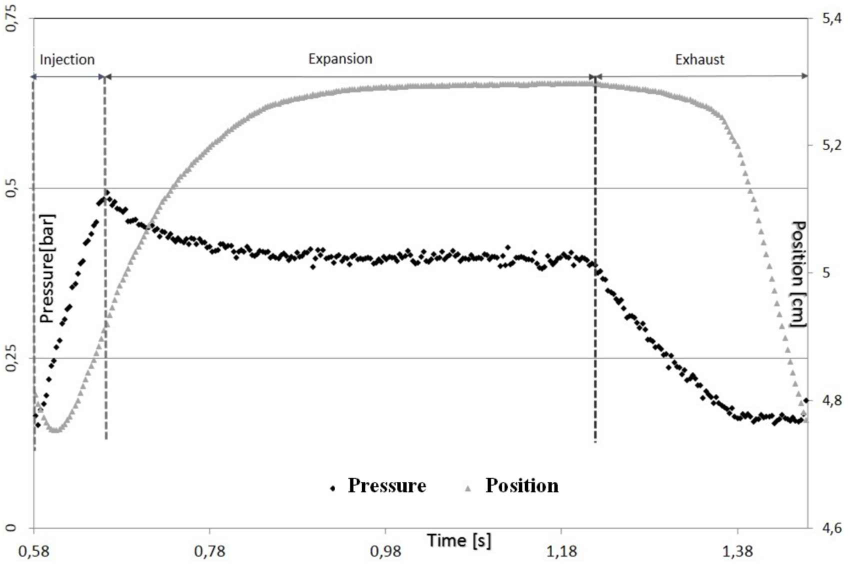

Fig. 7. Relative pressure and bellows displacement as a function of time for a single input/output valves opening/closing cycle.

Fig. 7 also reminds the previously described valves cycle, the total period cycle is equal to 0.873 s, which represents an engine frequency of 1.145 Hz.

Table 2. Strokes and times

Type of stroke	*Stroke [mm]*	*Time [ms]*
Injection	1	78
Expansion	5	549
Exhaust	6	246

The low frequency allows the injection phase to be really shorter than the exhaust one. It appears that the exhaust phase is long enough so the initial pressure is reached before the end of the exhaust phase[9]. The expansion phase is the longest one because the pressure quickly reaches its stabilized value which doesn't move faster the mobile part, the important dead-volume could explain that situation. Note that the displacement is quite weak regarding the initial position which means that the dead volume is important. Reducing the dead volume thanks to the mobile piece VM should enhance the chamber performance.

4.2 Introduction to a comparison between experimental and theoretical

The results of similar experiment have been compared to numerical simulation and have showed a good agreement [15] and are presented in Fig. 8. The model used for the simulation is a zero dimension one based [19] on a filling and emptying method. It is interesting regarding the energy conservation and state equation in each subsystem, the mass conservation throughout the whole machine completed with a Saint-Venant equation applied to the valves. So the model is dynamic and implemented with a bond graph formalism. The 8.3 Hz cycle is composed by injection time of 80 ms, followed by a 15 ms expansion time and so, a 25 ms exhaust time.

One can note two slight differences between experimental and numerical results. Firstly, there is a light delay on the sequence due to the non-instantaneous valves opening as in the simulation. Secondly there is an offset between the experimental and theoretical pressure that results from the

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[9] For example, in this case it could be possible to increase the spring stiffness to help to accelerate the exhaust.

difficulties to match the minimum load value of the simulation with that of the experimental test bench.

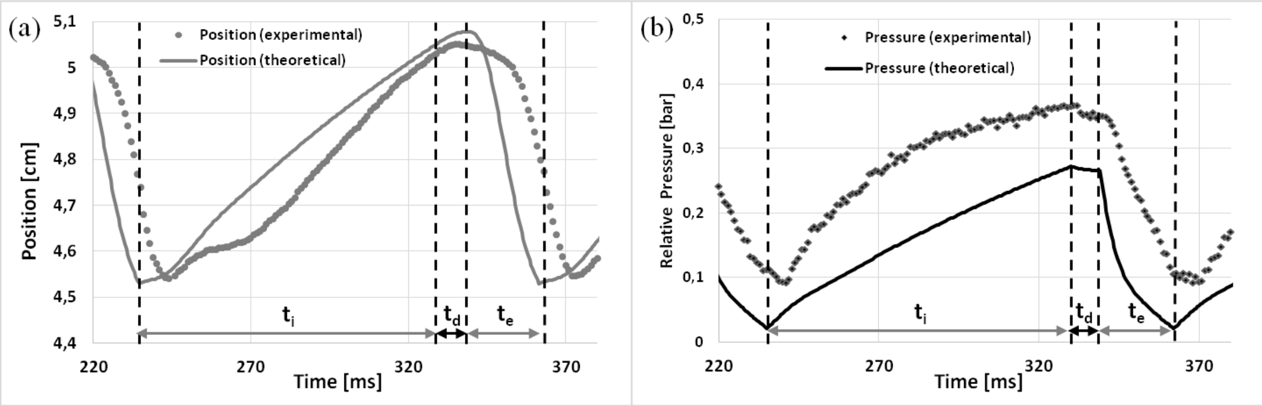

Fig. 8. Comparison between the theoretical and experimental results for position of the bellows' bottom (a) and the bellows' pressure (b) for a single expansion-compression cycle.

So, as taking into account that the bellows has a minimum length of 47.5 mm and a maximum length of 53 mm, the assumption of an average 50 mm length is made. It gives a possibility to estimate the volume using the position obtained on Fig. 7 for each recorded pressure data. The pressure evolution versus volume during the expansion phase seen on Fig. 6 can thus be plotted (Fig. 9).

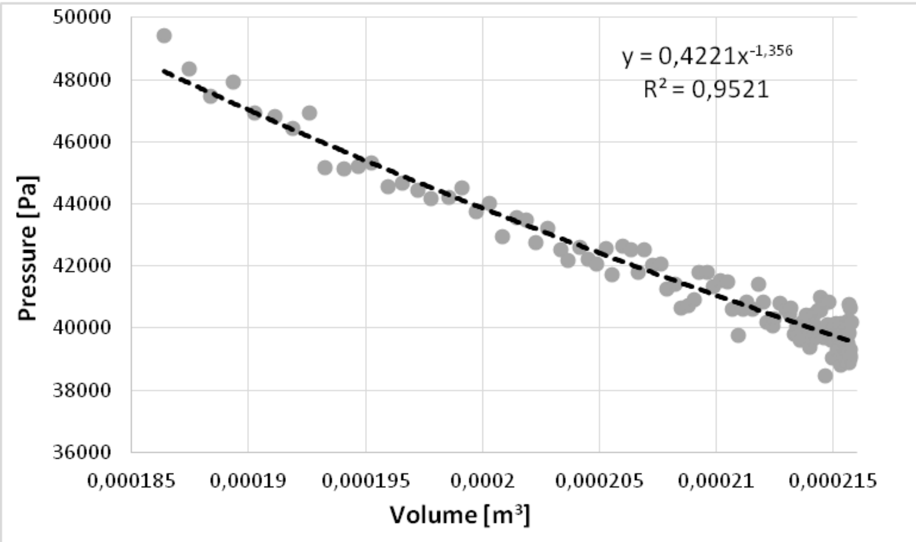

Fig. 9. PV diagram of the expansion time with a dead volume of 0.2 L

The experimental results of pressure versus volume enable to determine the polytropic coefficient of the evolution assuming that the process follows a polytropic law. In the presented case, the polytropic coefficient is found to be of 1.36 (Fig. 9). That result is also in accordance with our expectation of an adiabatic process of the air when the bellows is not heated. Following those first results a more complete test bench has been built incorporating a heater, a bigger load and in the future a bellows compression chamber to characterize the expansion chamber behaviour in a realistic environment.

Conclusion

The IndEHo's project led by ASSYSTEM aims to develop a new type of engine based on the Ericsson or Joule-Brayton cycle where expansion and compression piston's chambers have been replaced by metal bellows. Such engine should be more flexible regarding the work to provide or the load applied onto it. In order to characterize the behaviour of the bellows as an expansion (or compression) chamber, a test bench has been built in collaboration with the FEMTO-ST Institute. The next generation of bench should enable to experimentally determine the polytropic factor of the evolution of the heated gas within the bellows. Several parameters can be controlled such as the opening time of the intake and exhaust valves, the entrances pressure and temperature and the load applied on the bellows so that working conditions and the matching of the bellows can be determined for a better analysis development. These first results, even if improvable, have shown that an adiabatic behaviour is appropriate for a non-heated expansion chamber. These results have also enabled to validate a first simulation code for the bellows chamber behaviour. An improved of the test bench is currently under construction to allow tests with a heated expansion chamber and to determine if the engine behaviour could get closer to that of an Ericsson cycle.

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