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EXPERIMENTAL STUDY OF THE OPERATION CONDITIONS OF STABILITY ON A GAMMA STIRLING ENGINE

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ABSTRACT

Considering Stirling engines modern applications and cogeneration recovery energy from industrial process, the power of a Stirling prime mover is to be provided at a speed of rotation adapted to the operation of the receiver system (usually a generator) to exploit the performance of this machine under the conditions of its use (ie lowering of the rotational speed and torque transmitted rise or, more rarely, elevated speed and lowering the torque transmitted). Knowing that the hot air engine cannot change speed quickly and in order to have a well designed system, it is important to study the unsteady state conditions. In this work we present an experimental stability analysis of an irreversible heat engine working at different conditions. The experimental study aims at analyzing the effect of working parameters disruption on the stability of the Gamma Stirling engine. Parameters involved in this experimental study are the load pressure of the motor and the load applied to the Stirling engine. The influence of engine operating parameters on its torque and rotational speed is investigated. The time required by a gamma type Stirling engine to stabilize operation after disruption is estimated. Results show that after a small disruption, speed and temperature evolutions decays exponentially to the steady state determined by a relaxation time. It is assumed that the decrease of the applied power load to the engine or the increase of the load pressure leads to a speed up. And that the increase of the applied power load to the engine or the decrease of the load pressure leads to a speed down.

KEYWORDS: Stirling engine, Disruption influence, Performances variations, Stability conditions, Relaxation time.

INTRODUCTION

Major studies in literature of Stirling engine focused on steady state energetic proprieties. Only few researches aim at analyzing the stability of the engine numerically. However, the stability analyses described in literature are not validated experimentally. Numerically, Ladino-Luna et al. [1] investigated local stability of thermal engines modeled as an endoreversible Curzon and Ahlborn cycle when a non-linear heat transfer law is assumed.

Huang et al.[2] studied the local stability of a non-endoreversible heat engine working between the maximum power output and the maximum efficiency is analyzed based on stability criteria for almost linear systems. They defined an internal irreversibility factor I. When I=1, the engine is endoreversible. When 0<I<1, the engine is internally irreversible. Reyes-Ramírez et al. [3] presents a global stability analysis of a Curzon–Ahlborn heat engine considering different regimes of performance: maximum power (MP), efficient power (EP) and the so-called ecological function (EF). Sanchez-Salas et al.[5] extended a previous work and studied the local stability of an endoreversible Curzon-Ahlborn engine working in the ecological regime, with inclusion of the engine inherent time delays to account for internal irreversibilities. Besides, in order to compare the ecological and maximum power regimes, they included a third criteria named Maximum efficient power. Barranco-Jimenez et al. [4] showed that the relaxation times are function of the temperature ratio $\tau = T_2 / T_1$ with T2>T1, the cost function f and the parameter R (a parameter related to the degree of internal irreversibilities). They observe that the stability of the system improves as τ increases whereas for changes in f and R. Barranco-Jimenez et al. [6] carried out a thermoeconomic optimization of an irreversible solar-driven heat engine model by using finite-time/finite-size thermodynamic theory. They take into account losses due to heat transfer across finite time temperature differences, heat leakage between thermal reservoirs and internal irreversibilities in terms of a parameter which comes from the Clausius inequality.

Any thermal engine is exposed to continuous internal and external perturbation while operating. This experimental study measure the time required by a Gamma Stirling engine to operate on a stable operation speed changes during the intervention of different parameters to its initial stable condition. The parameters involved in this experimental study are the load pressure of the motor and the load applied to the Stirling engine. This experimental study aims to determine the influence of engine operating parameters on its torque and rotational speed. The time required by a gamma type Stirling engine to stabilize operation avec perturbation will be estimated.

NOMENCLATURE

P1 : Pressure before disruption
P2 : Pressure after disruption
ΔN : speed variation
P_{load} : Applied power load to the engine
C_1 : torque before disruption
C_2 : torque after disruption
Pu_1 : output power before disruption
Pu_2 : output power after disruption
N_1 : rotational speed before disruption
N_2 : rotational speed after disruption

EXPERIMENTAL FACILITY AND METHODOLOGY

A Gamma type Stirling engine will be investigated in this study. It uses air as working fluid and can deliver a maximum output mechanical power of about 500 W. Its maximum rotation speed is around 600 rpm when the maximum working pressure is about 10 bar. This engine is mainly composed of a compression cylinder (C), an expansion cylinder (E) and three heat exchangers (heater, regenerator, cooler). The regenerator (R) is a porous medium (i.e., made of stainless steel with 85% porosity). In the real engine, the cooler (K) acts as a cold source heat exchanger formed by an open water circuit and the heater consists of 20 tubes in order to increase the exchange surface between the working gas and the hot source (H). In the modelling assumptions, the hot source of the Stirling engine is the expansion cylinder wall and the cold source is the compression cylinder wall (cf. Figure 1a). The geometric properties of this Stirling engine are presented in previous studies of Gheith et al. [8–11], with some experimental investigations. In particular, the influence of initial filling pressure, engine speed, cooling water flow rates and heating temperature on the engine performances (brake power and efficiency) has been highlighted. More recently, Hachem et al. [12] presented a global energetic modeling of the same Stirling engine. They showed that the engine rotation speed have an optimum value that guarantees the best Stirling engine performances. For low rotation speeds, the brake power increased with rotation speed, whereas for high rotation speeds, the brake power decreases when the rotation speed increases. The increase of initial filling pressure leads to an increase of working fluid mass. The increase of hot end temperature leads to an increase of the thermal exchanged energy. These two phenomena cause the increase of the engine brake power. The authors demonstrated that engine brake power is also sensitive to its heat exchanger efficiency. The engine regenerator is the most influencing component.
Several type-K thermocouples with a diameter of 0.5, 0.25, and 0.0254mm were used to measure the temperature at different locations of the engine. Because the interest was to measure the instantaneous temperatures, proper care has been taken regarding the size and the thermal inertia (which should be very low) of the thermocouples. Two thermocouples were mounted upstream of the expansion and compression spaces, respectively. Other two thermocouples were used to measure the inlet and outlet temperatures of the water supplying to the cooler. Eight thermocouples are implemented to measure the temperature of the working gas passing through the symmetrical side of the regenerator matrix (figure 2). The thermocouples were skinned up to 1mm in the regenerator matrix without touching the material.
The Stirling engine drives an alternator (figure1.a) which feeds a load consisting of a series of lamps 10 (figure1.b) connected in parallel to each electric resistance 55W. The first experimental test is to switch on lamps even to accelerate or to decelerate the engine. The second experimental test is to change immediately the filling pressure of the engine using an external compressor (figure1.c) allowing a constant pressure inside the engine. The two different tests aim at describing the temporal evolution of temperature and speed excitement after a disruption of the operating steady state to analyze the effect of an operating parameter brusque variation on the stability of the operating steady state of the Stirling engine and determine the

time required to regain steady state is calculated in each experiment.

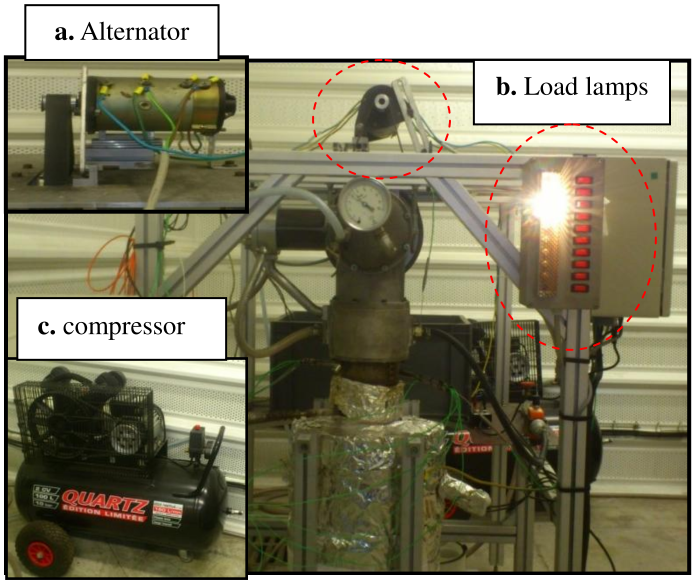


FIGURE 1. EXPERIMENTAL SETUP OF THE GAMMA STIRLING ENGINE

FIGURE 2. REGENERATOR INSTRUMENTATION (8 THERMOCOUPLES ARE POSITIONED IN THE REGENERATOR)

STABILITY ANALYSIS

Different experiments were performed to collect the performance of the Stirling engine at different working conditions. The effects of two types of disruption even to speed up or to speed down the engine are investigated experimentally. The first disruption is the dissipated load at the output of the engine and the second disruption is the filling pressure.

Disruption 1: Dissipated load at the output of the engine

In this section, we study the response of the machine to the power required by the alternator. we discuss the operation of the Stirling engine for different braking power applied to the piston.

Initially the engine is working at an initial constant steady state regime for which the torque is C_1, the output power is Pu_1, the rotation speed is $N_1$and no dissipated load power is connected to the alternator. Then a sudden change of the dissipated load power is done when switching on load lamps. Experimental tests are described in table 1. Cases from 1 to 5 in tables 1 and 2 are a speed up tests and cases 6, 7 and 8 are slow down tests. Evolutions of speed (figure 3 and 6) and temperatures (figure 4 and 5) are recorded until attending the final steady state of the system. Initially the engine presents the same behavior for the five different cases. During the starting of the disruption, the engine is forced to speed up and all the functioning parameters such as pressure, temperatures and speed follows an exponential evolution until the new steady state is reached. The stability of the system improves as the intensity of the brusque disruption decreases. The relaxation time depends on the intensity of the brusque disruption.

From figure 3, we can understand that the relaxation time increased slowly as the intensity of the brusque disruption increases this implies that the reduction of the applied power load to the engine improve the system stability.

From figures 4 and 5, it is seen that Engine acceleration results in an increase of the temperature inside the compression cylinder (cold side) and a decrease of the temperature inside the expansion cylinder (hot side).

From table 2, it is seen that the produced torque of the Stirling engine decreases after a speed up and increases after a speed down of the engine. When increasing the engine rotation speed, its performances are deteriorated (decrease of its total efficiency and the produced power of the engine) because of increased friction losses. In case 5, the engine speed increases from the initial angular velocity of 431 rpm to 523rpm in 140s. compared to the traditional Stirling engine, the present engine takes longer time to reach the steady state regime. This is because leakage losses in the engine.

TABLE 1. DESCRIPTION OF MAIN TEST BY CHANGING THE DISSIPATED LOAD POWER

Case	ΔN(rpm)	P_{load} (W)	Description
1	7.4	75	Speed up
2	52.3	150	Speed up
3	81.8	225	Speed up
4	84.2	300	Speed up
5	92	375	Speed up
6	-75.6	0	Speed down
7	-82.1	0	Speed down
8	-90.9	0	Speed down

TABLE 2. EXPERIMENTAL TESTS WHEN CHANGING THE DISSIPATED LOAD POWER OF THE ENGINE

Case	C1 (Nm)	C2 (Nm)	Pu1 (W)	Pu2 (W)	N1 (rpm)	N2 (rpm)
1	3.83	3.47	168.20	158.35	434.5	441.9
2	3.95	3.34	173.22	164.68	428.7	481
3	4.08	3.36	177.61	175.50	426.3	508.1
4	4.04	3.49	178.75	183.19	430.2	514.4
5	4.05	3.45	177.82	185.26	431	523
6	3.76	4.08	166.35	173.49	518.9	428
7	3.34	4.04	174.29	176.75	510.1	428
8	3.42	4.08	179.43	178.79	503.6	428

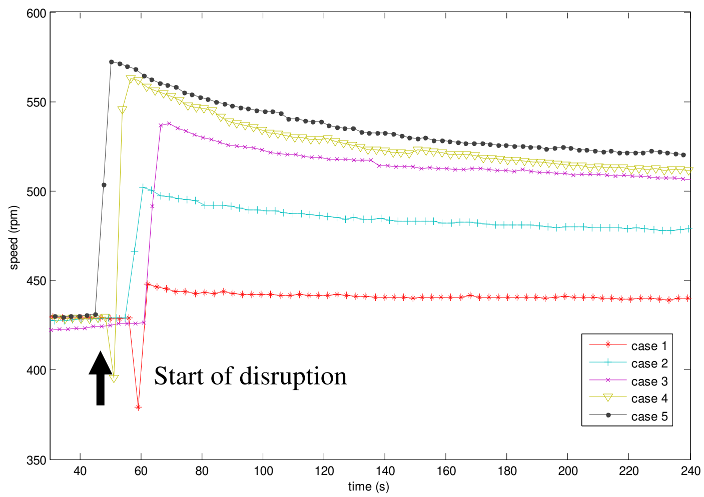


FIGURE 3. TEMPORAL EVOLUTION OF SPEED UP WHEN CHANGING THE DISSIPATED LOAD POWER

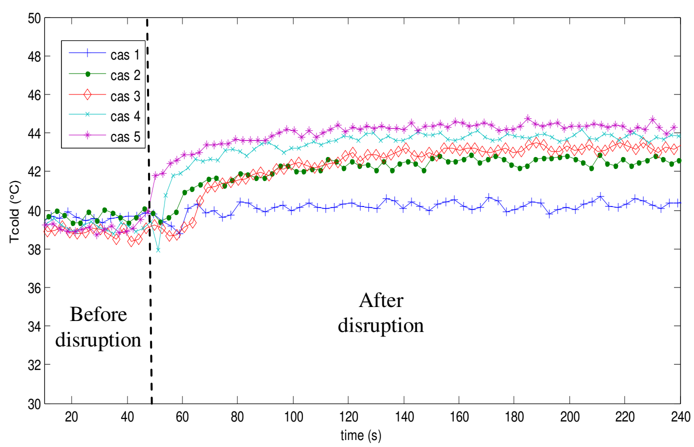


FIGURE 4. TEMPORAL EVOLUTION OF THE TEMPERATURE OF THE COLD COMPRESSION CYLINDER (SPEED UP WHEN CHANGING THE DISSIPATED LOAD POWER)

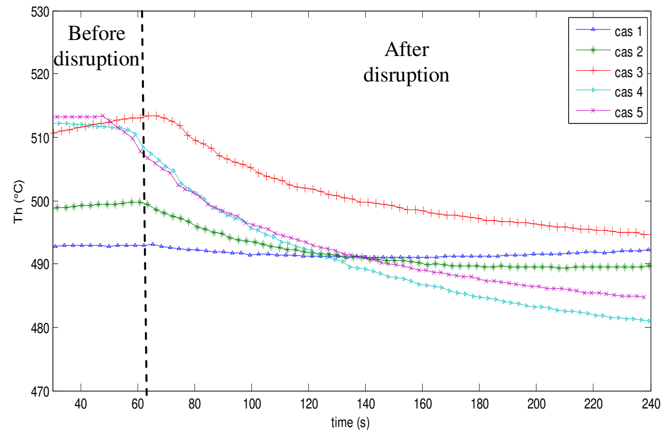


FIGURE 5. TEMPORAL EVOLUTION OF THE TEMPERATURE OF THE HOT EXPANSSION CYLINDER (SPEED UP WHEN CHANGING THE DISSIPATED LOAD POWER)

When decreasing the dissipated load power applied to the alternator, the rotational speed of the Stirling engine decreases (Speed down). The system decays from an initial steady state to the same final steady state for different rotational speed slow down cases (figure 6).

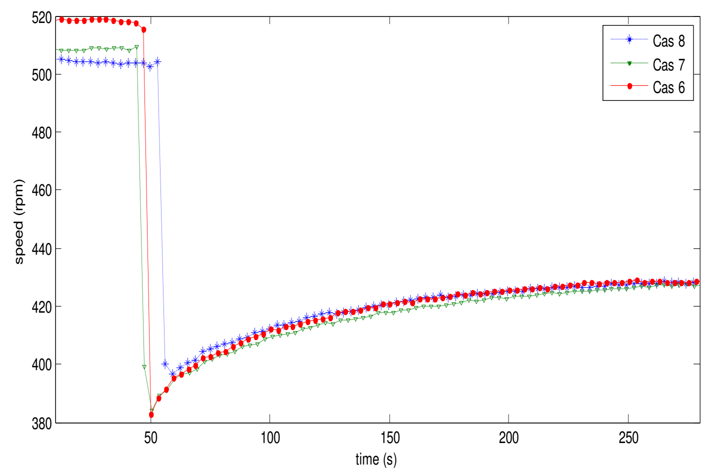


FIGURE 6. TEMPORAL EVOLUTION OF SPEED DOWN WHEN CHANGING THE DISSIPATED LOAD POWER

Disruption 2: the filling pressure of the engine

Perturbation of the initial filling pressure: during this experience the heating temperature is about 500°C, le cooling water flow rate is about 7 l/mn and the initial filling pressure is suddenly changed either increase or reduction. Different experimental tests are described in table 3

At a sudden increase of engine's filling pressure: the disruption applied to the initial steady state takes about 16 minutes before attending the final steady state. The intensity of perturbation didn't change the relaxation time needed to reach the final steady state. But the speed increases even when increasing the intensity of the filling pressure disruption. It is clearly seen (figure 7) that once the disruption begins, speed increases immediately from 350rpm to 420rpm in case 4. But it decreases due to irriversibilities inside the engine and finally regains its peak value about 420rpm. The transient state is characterized by two phases. it can be observed that the speed value in the final steady state periode is equal to its pic value at disruption (figure 7). During the first phase the temperature decreases due to the increase of filling pressure which means an increase of the filling mass of air inside engine. During the second phase, which lasts longer than the first phase, the introduced cold mass of air takes a lot of time to warm up. Thermocouples TR1 and TR5 are closer to the disturbance that is why their intensity of variation are higher than the temperature variation recorded by thermocouplesTR4 and TR8 (figure 9). Having regard to the introduction of a cold mass of air into the engine, its speed decreases over time (phase 1). Once the temperature of the introduced air increases, the engine speed increases gradually (phase 2) until reaching the steady state regime. After a small perturbation, the system decays exponentially to the steady state characterized with the relaxation time.

TABLE3. DESCRIPTION OF MAIN TEST BY CHANGING THE FILLING PRESSURE

Case	P1 (bar)	P2 (bar)	ΔT_{cold}	ΔT_{hot}	Description
1	3	4	2	-13	Speed up
2	3	5	5	-34	Speed up
3	3	6	7	-52	Speed up
4	3	7	9	-62	Speed up
5	3	8	9	-52	Speed up
6	4	3	-	-	Speed down
7	5	3	-	-	Speed down
8	6	3	-	-	Speed down
9	7	3	-	-	Speed down

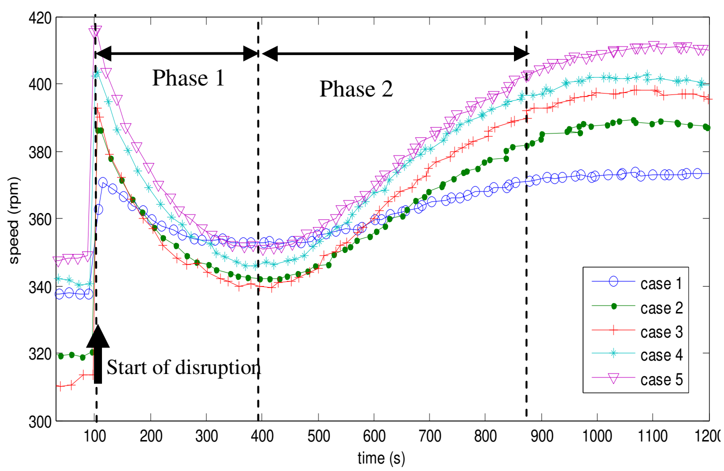
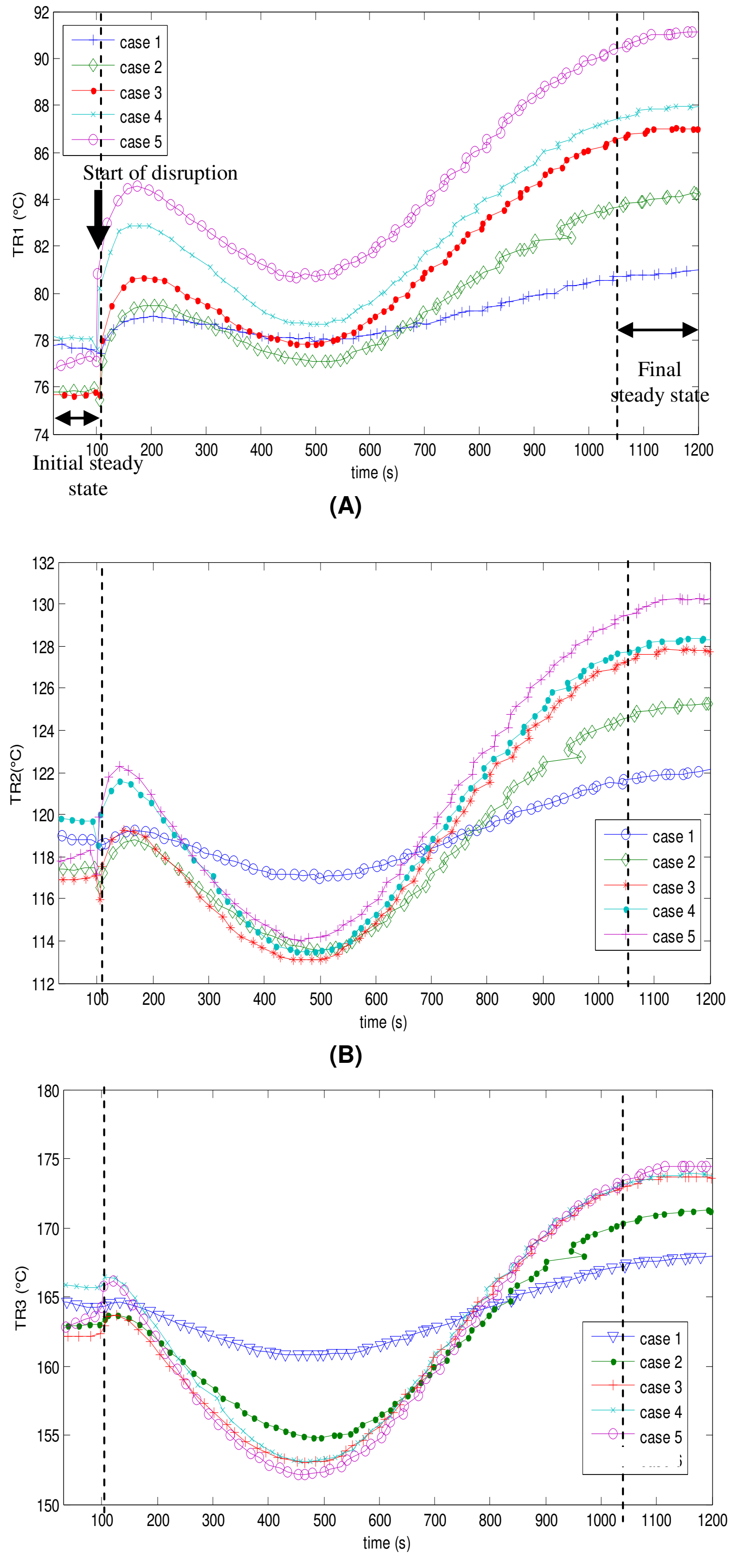
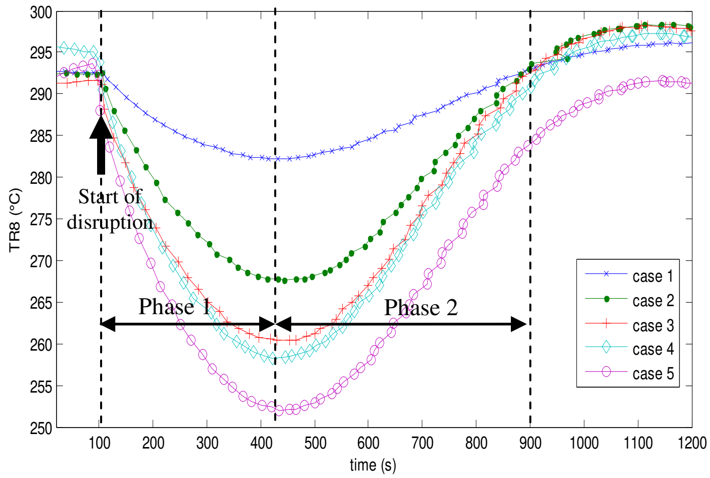


FIGURE 7. TEMPORAL EVOLUTION OF SPEED UP BY CHANGING THE FILLING PRESSURE



(C)



(D)

FIGURE 8. TEMPORAL EVOLUTION REGENERATOR TEMPERATURE : (A)T_{R1} (B) T_{R2} (C) T_{R3} (D) T_{R8} (SPEED UP WHEN CHANGING THE FILLING PRESSURE)

At a sudden decrease of engine's filling pressure: the rotation speed of the engine decreases immediately and risks packing the shaft work of the engine. Then return to each initial value and decay exponentially until reaching the final steady state speed value. In case 4, speed decays from about 390rpm to 318 rpm (figure 9). When lowering of the rotational speed, temperature evolution inside regenerator has inverse its evolution when increasing the engine (figure 10). Directly after the starting of the disruption, a great difference between cases is clearly seen, but once the final steady stade is reached, these differences are reduced as fig 9-10 and 11 illustrates.

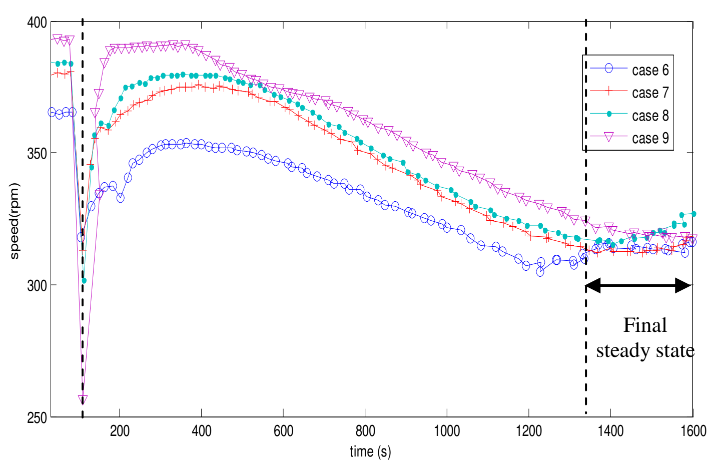
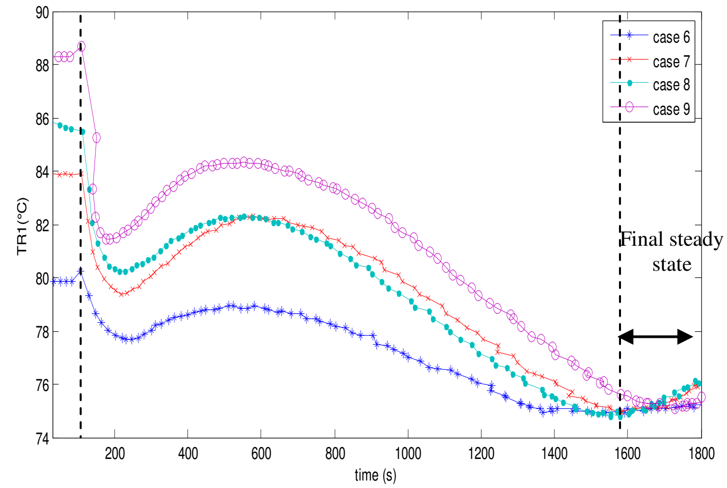
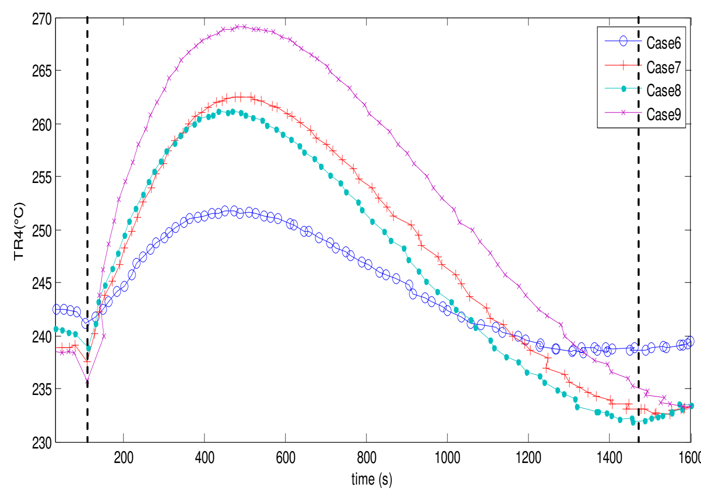


FIGURE 9. TEMPORAL EVOLUTION OF SPEED DOWN WHEN CHANGING THE FILLING PRESSURE



(A)



(B)

FIGURE 10. TEMPORAL EVOLUTION OF REGENERATOR TEMPRERATURE : (A)T_{R1} NEAR THE COLD COMPRESSION CYLINDER (B)T_{R4} NEAR THE HOT EXPANSION CYLINDER (SPEED DOWN WHEN CHANGING THE FILLING PRESSURE)

CONCLUSION

The Stirling engine is exposed to continuous internal and external perturbations while operating. But the hot air engine cannot change speed quickly. This analysis guarantees an experimental dynamic behavior of the engine like stability and relaxation time. The stability of the system improves as the intensity of the brusque disruption decreases. The relaxation time depends on the intensity of the brusque disruption.

Not only working parameters disruption affects the engine's stability, geometrical characteristics of each part and physical proprieties of the working gas used in the engine act on its possibility to change its regime from a steady state to another.

Irreversibilities inside Stirling engine increases when changing its functioning regime.

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