Discussion of the Effects of Recirculating Exhaust Air on Performance and Efficiency of a Typical Microturbine

Ward De Paepe[a*], Frank Delattin[a], Svend Bram[ab], Jacques De Ruyck[a]

[a]Vrije Universiteit Brussel, Dept. of Mechanical Engineering (MECH), Pleinlaan 2, 1050 Brussel, Belgium

***Corresponding author:** e-mail: wdepaepe@vub.ac.be, Tel: +32-2-6293182, Fax: +32-2-6292865

[b]Erasmushogeschool Brussel

Dept. of Industrial Sciences and Technology, Nijverheidskaai 170, 1070 Brussel, Belgium

Abstract:

This paper reports on a specific phenomenon, noticed during steam injection experiments on a microturbine. During the considered experiments, measurements indicated an unsteady inlet air temperature of the compressor, resulting in unstable operation of the microturbine. Non-continuous exhaust air recirculation was a possible explanation for the observed behaviour of the microturbine.

The aim of this paper is to investigate and demonstrate the effects of exhaust recirculation on a microgasturbine. Depending on wind direction, exhaust air re-entered the engine, resulting in changing inlet conditions which affects the operating regime of the microturbine.

For this paper, a series of experiments were performed in the wind tunnel. These series of experiments allowed investigation of the effect of the wind direction on flue gasses flow. Next to the experiments, steady-state simulations of exhaust recirculation were performed in order to study the effect of exhaust recirculation on thermodynamic performance of the microturbine. Dynamic simulations of the non-continuous recirculation revealed the effects of frequency and amplitude on average performance and stability.

Results from simulations supported the important impact of exhaust recirculation. Wind tunnel tests demonstrated the influence of the wind direction on recirculation and revealed the necessity to heighten the stack, thus preventing exhaust recirculation.

Keywords:

Microturbine; performance; exhaust air recirculation; wind tunnel experiments; wind direction

Nomenclature:

Abbreviations:

ABL Atmospheric Boundary Layer

CHP Combined Heat and Power

EGR Exhaust Gas Recirculation

NGCC Natural Gas-fuelled Combined Cycle

TIT Turbine Inlet Temperature

Symbols:

a sound speed (m/s)

Fr Froude number

g gravitation constant (= 9.81 m/s^2)

L Characteristic length (m)

Ma Mach number

Re Reynolds number

U Mean wind velocity (m/s)

Greek symbols:

ρ density (kg/m^3)

μ viscosity (kg/m/s)

1 Introduction

Microturbines are small scale combined heat and power (*CHP*) applications with limited power output (50 to 500kWe). By changing the shaft speed in combination with the fuel flow, the engine control keeps the electric power output constant at a constant *TIT* (Turbine Inlet Temperature), in order to maintain a maximal electric efficiency. In steady-state conditions, the machine parameters may not change too much, so the shaft speed should remain more or less constant. However, during the steam injection test on the T100 installed at the VUB thermodynamics lab [1], a very unsteady operation of the microgasturbine was observed. Partial exhaust gas recirculation was believed to cause this phenomenon.

Exhaust Gas Recirculation (*EGR*) on gas turbines in combined cycle has been investigated in the past by means of simulations and experiments. Some of the advantages of *EGR* are the higher CO_2 concentration in the exhaust air and the lower flue gas mass flow, which makes post-combustion amine-based carbon capture more economic feasible by natural gas-fuelled combined cycle (*NGCC*) [2-5]. Research has shown that, compared to a cycle without *EGR*, a recirculation ratio of 50% could increase CO_2 concentration from 3.8mol% to 7.9mol% and reduce the mass flow of flue gasses, fed to the absorber, by 51.0% [4, 5]. With oxygen enrichment, the *EGR* ratio could principally be further increased [4, 5]. Experiments on a GE Dry Low No_x gas turbine combustor at *EGR* ratios of 30% [6] and 35% [7] showed an operation with high efficiency and determined CO_2 levels of more than 8Vol% [6] and 10Vol% [7]. It is predicted that with only minor modification, the combustor can be operated with *EGR* levels above 40% [7]. It has also been demonstrated that NO_x emissions decrease with increasing *EGR* levels, by more than 50% at an *EGR* ratio of 35% [7]. The CO emissions however are a limiting factor for *EGR*. However a flame can be sustained at O_2 concentration as low as 14mol%, the levels of unburned hydrocarbons and CO become excessively high when the O_2 concentration reaches 16mol% [8], which indicates that an *EGR* ratio exceeding

40% could be difficult to achieve for the combustor [2, 5]. Based upon the advantages of *EGR* and the recommendations formulated by different researchers, different novel types of *NGCC* with post-combustion CO_2 capture using a 40% *EGR* ratio, have been presented in literature [9-14].

The secondary positive effect of Dry-*EGR*, the reduction of NO_x-emissions, has recently been studied in microgasturbine combustors by means of CFD simulations [15-17] and experiments [18]. Both experiments and simulations indicated the potential to control NO_x emissions by exhaust gas recirculation.

In our case however, the exhaust gas recirculation is a random, uncontrollable and unwanted phenomenon, which causes an unstable operation of the microgasturbine and should therefore be prevented.

2 Approach

The T100 microturbine was installed in 2002 at the VUB. The T100 is connected to the power grid of the campus and injects its thermal power in the campus district heating system. Some general data about the T100 microturbine is given in Table 1. Fig. 1 shows the air intake and the two stacks of the T100. The exhaust and ventilation stack are located directly above the air intake of the microturbine. It is believed that the flows from these stacks are forced down due to the turbulence caused by the surroundings and the suction generated by the air intake; especially when wind comes from across the building and separates at the end. The surroundings of the building equipped with the T100 (Building Z) can be seen in Fig. 2.

The aim of this paper is to investigate and demonstrate the effects of exhaust recirculation on a T100 microgasturbine by simulations and to find a solution to prevent exhaust recirculation by experiments.

In a first step, the results of the measurements with steam injection were examined in order to find proof of the hypothesis of exhaust gas recirculation. Correlations between the data were calculated. In a second step, the effect of exhaust air recirculation on the global efficiency in steady-state regime was examined, using the ASPEN® plus process simulator (Version 2006.5). For these simulations, a previously developed model was used [19]. As a third step, the effect of the non-continuous exhaust gas recirculation on the T100 was studied, using a dynamic simulation model of the T100 in Simulink® [20]. The step response of the engine control unit was simulated, in order to study its response on changing inlet conditions. The effect of frequency and amplitude of the recirculation on the overall performance of the T100 was also studied. In a fourth and final step, a set of experiments were carried out in the industrial wind tunnel at the Fluid Mechanics lab at the VUB. In the tunnel, the Atmospheric Boundary Layer (*ABL*) was recreated at scale, using well-known techniques. After creating this ABL, a scale model of the building where the T100 is installed as well as the surrounding buildings were placed in the tunnel to study the influence of the wind speed and direction on the exhaust gas recirculation. The aim of the wind tunnel experiments was to find a solution that would prevent the exhaust gas recirculation. The wind tunnel tests demonstrated the required renovations and adaptations to improve the current microturbine plant setup.

3 Problem description

3.1 Dry operation

Fig. 3 gives a good visualization of the occurring problem. As a result of the non-constant inlet air temperature, the power generated by the microturbine changes rapidly and the engine control has to interfere continuously to keep this produced electrical power constant. Fig. 3 shows the effect of the fluctuations of the inlet air temperature on the produced power. A rise in inlet temperature results in a lower produced power. To keep the power constant, the engine control will speed up the microturbine to restore the constant power output. On the other hand, a lower inlet air temperature results in a higher electrical output, so the microturbine has to be slowed down. Unfortunately, the shaft speed is recorded by the engine monitoring system only every 90 seconds, making it difficult to see these changes.

The real influence of the inlet air temperature on the produced power can be seen by calculating the correlation between both signals. Fig. 4 gives the correlation between the inlet air temperature and the produced electrical power, for different time lag values.

As expected there is a negative correlation: a rise in inlet air temperature has a negative effect on the produced power. The correlation curve shows a maximum for 3 seconds lag and indicates that there is a strong correlation between both. The probability that this correlation is due to random noise is nearly zero and thus far below the value of 0.05 which indicates that there is, as expected, a real correlation between the inlet air temperature and the produced power [21] because of the physical link between both. The maximum correlation at 3 seconds time lag is probably due to the time it takes for the air to travel through the air intake channel and the microturbine itself. The inlet air temperature is measured at the entrance of the air intake (at the air filter), but the air still has to flow through 8 meters of channel in our particular setup before it enters the T100 engine.

3.2 Wet operating

Due to the changing inlet temperature, the pressure after the compressor will change. When hotter air enters the compressor, the pressure after the compressor will drop. During steam injection experiments [1], this lead to a non-constant steam flow (Fig. 5.). The steam flow from the steam boiler to the compressor outlet duct is governed by the pressure difference between the steam boiler and the compressor exit. Pressure in the steam generator is set higher than the pressure behind the compressor. Once the pressure in the steam generator is higher than the pressure behind the compressor, steam will be injected. When the pressure behind the compressor falls, the steam flow will rise, because of the rise in pressure gradient (the pressure in the steam boiler remains constant).

The higher inlet air temperature and higher amount of injected steam into the microturbine counteract on the electric power output. A higher inlet temperature will result in a lower power, while a higher steam injection flow will result in a higher power output. The question however is whether the higher steam injection ratio can compensate the loss in power due to the rise in inlet temperature.

On Fig. 6, the variations in the inlet temperature are plotted against the produced power for an engine run with steam injection. The produced power is still influenced by the changing inlet air temperature, but the spikes are smaller, due to the compensation through enhanced steam injection.

Fig. 7 represents the correlations between inlet air temperature and produced power on the one hand and between inlet air temperature and injected steam mass flow on the other hand. Again, the correlation for the produced power is negative and reaches a maximum for a 5 seconds time lag, which is a slightly bigger lag than without steam injection. Steam injection has a positive correlation, due to the lower pressure with higher inlet air temperature. The correlation reaches a maximum after 2.7 seconds. The difference between the maximum can be explained as follows: the injection steam flow is only function of the pressure after the compressor, while the produced power is function of different parameters that are affected by the changing inlet temperature.

4 Simulations of the exhaust air recirculation

4.1 Steady-state simulations

For the steady state simulations, a previously developed ASPEN® model was used [19]. The ASPEN® model consists of a compressor, turbine, recuperator and combustion chamber.

Representative generic compressor and turbine characteristics are introduced in the process simulator in order to obtain both design and off design behaviour. Validation of this model was done by De Paepe et al.[1]. In this approach, part of the exhaust gas is first cooled down to a certain value before it is rerouted to the air intake. Exhaust recirculation had to be simulated in this way, because in reality the exhaust flow is not entirely recirculated to the engine, but first has to travel through the outside air, where it is cooled down.

Due to the exhaust gas recirculation, combustion products enter the inlet air. On Fig. 8, the increasing share of the combustion product in the inlet air is given. Fig. 9 shows the influence of the recirculation of the exhaust gasses on the electric efficiency of the microturbine. As expected, the exhaust recirculation has a negative effect on the electric efficiency, due to the rising inlet temperature. The results are also compared with the results from simulations without recirculation. For this simulation, the same inlet temperature as for the recirculation was used, while the composition of the inlet air was kept constant (21mol% O_2, 79mol% N_2 and 0mol% CO_2 and H_2O), to demonstrate the effect of combustion products in the inlet air. Results of the steady-state simulations on Fig. 9 show that the loss in electric efficiency is not only the result of the rising temperature. Fig. 9 shows clearly that the presence of combustion products in the inlet air has a non-negligible influence on the microturbine performance, which has also been noticed by other researchers during simulations of a *NGCC* with *EGR* [10]. The amounts of work and heat to compress and heat these inert components (H_2O and CO_2) have a noticeable part in the efficiency loss. This conclusion is important for the validation of the microturbine's simulation models. Within these models, the composition of the inlet air is kept constant (dry air). This will result in an overestimation of the microturbine's efficiency once recirculation occurs. Changing the composition of the inlet air of the compressor in the simulation is easy; however it is hard to model the recirculation process, because it happens randomly and non-continuously. Moreover, it is hard to predict the behaviour of the exhaust flow regarding cooling and flow pattern. Only by online monitoring the inlet air composition, the right composition can be obtained for the simulations. However, the question that remains is: ‘Will the electric efficiency depend on the frequency or amplitude of the exhaust air recirculation, or will averaging give the exact value?’

4.2 Dynamic simulations

Steady-state simulations have shown the influence of the flue gas recirculation on the electric efficiency of the microturbine. The recirculation is however not a continuous process, but depends on the wind direction and the presence of vortices in the wind (see Section 6.**)**. Two series of simulations on the dynamic behaviour of the microturbine have been performed. First, the step response of the engine control unit on a change in inlet air temperature and composition was studied, using a dynamic model of the microgasturbine in Simulink® [20]. A white box model of the microturbine was built in Simulink. Recuperator, compressor and turbine are considered quasi-static; however the inertia of the axis and the thermal inertia of the recuperator are taken into account. For the modulation of the compressor and turbine, generic maps were used.

Fig. 10 gives the result of the step response simulations. Steps of 1, 2, 5 and 10% of recirculated exhaust air in the inlet air are simulated. For the fuel flow rate, at the step time (= 500s), fuel consumption drops, along with the power production and the electric efficiency, due to the sudden change in inlet air temperature and composition. The controller will interfere and speed up the machine, by giving more fuel to the combustion chamber, as can be deducted from Fig. 10. The electric power will rise again, until the requested output has been reached. Due to the change in inlet air temperature and composition, the microturbine will consume more fuel to produce the same amount of electric power, resulting in a lower electric efficiency. The higher the recirculated part in the inlet air, the lower the efficiency will be after the step, which is in complete agreement with steady-state simulations. Depending on the step height, the controller needs more time to restore the steady-state condition. For a step of 5% exhaust air in the inlet air, the controller needs 100 seconds to restore the electric output.

A second series of dynamic simulations attempted to find an answer to the question that was posed after the steady-state simulations: 'Will the electric efficiency depend on the frequency or amplitude of the exhaust air recirculation, or will averaging give the exact value?' Or in other words: 'What is the influence of the action of the engine control unit on the average efficiency'. To answer this question, dynamic simulations over long periods were performed, where the inlet conditions changed periodically by changing the period, frequency and shape. For inlet temperature changes, simulations have shown that there was no difference between a dynamic simulation average and the same steady-state simulation.

Fig. 11 shows the results of the dynamic simulations of the exhaust recirculation in Simulink®. For this simulation, constant changing inlet conditions were applied. The amount of recirculated air was changed, using a square wave and a sine wave. After simulations, the average efficiency was compared with the efficiency at constant exhaust recirculation.

Fig. 11 shows that there is a small difference between the average efficiency of the square wave, compared to the constant recirculation. The higher the amplitude, the bigger the difference between the average efficiency of the square wave with different periods themselves and between the square waves and the constant recirculation becomes, however these differences are still small. With a shorter period, the controller has to interfere more during a certain fixed period. Every time the microturbine meets a wave front, the controller has to react and speed up or slow down the microturbine to reach the requested output power. During this transition, the microturbine is not working at maximal *TIT*, which results in a lower efficiency. So the shorter the period, the more the microturbine has to go through these transitions, the more the microturbine is working at a lower instantaneous efficiency, resulting in a lower average efficiency compared to the constant recirculation. When the amplitude of the square wave gets higher, the produced electrical power drops deeper, as can be seen on Fig. 10. The higher the amplitude, the further the microturbine is away from its requested produced power at the step time, so the controller has to speed up or slow down the microturbine faster. The faster the speed change happens, the further the machine is away from its optimal operating point and the longer it takes to reach this point again, resulting in lower average efficiency, compared to the continuous recirculation.

For the sine wave simulations, the same tendency can be observed as for the square wave, though the difference between non-continuous and continuous recirculation is now very large. The different behaviour for the different inlet signals can be explained by the actions of the controller. For the square wave, the controller only has to act at the front of the square, while with the sine, the controller has to interfere all the time. Because temperature and composition of the inlet air are changing continuously, the controller is aiming for a wrong set point, resulting in a microgasturbine that is not working at its optimal design point, which results in a lower efficiency. When comparing the sine wave efficiency with the efficiency of the constant recirculation, one can remark that the difference between both increases as amplitude highers, which can be explained by the slope of the curves. The more the amplitude of the wave increases, the faster the optimal operation point of the microturbine will change and the further the actual operating will be away from this optimal point, resulting in a larger decrease in efficiency. The same explanation can be used for the rising difference between the sine and square waves with rising amplitude, unlike the constant recirculation with the square wave, the inlet conditions change, so the controller has to act at the fronts of the wave. However, most of the time, the inlet conditions are still stable, resulting in a limited controller acting time. Thus the microturbine runs most of the time at or close to an optimal working point, which will limit the average efficiency loss, even at higher amplitude, compared to the sine wave were the engine control interferes all the time, resulting in a larger decrease in efficiency with rising amplitude. When looking to the sine wave only, one can see that with decreasing period at the same amplitude, the efficiency loss becomes larger. This again, can be explained by the slope of the curves. The more the amplitude of the wave increases, the faster the optimal operating point of the microturbine will change, resulting in a lower average efficiency.

4.3 Conclusion

Steady-state and dynamic simulations of the exhaust gas recirculation have been performed. Results show the non-negligible influence of the recirculation on the microturbine's performance.

Steady-state simulations showed that - except inlet temperature variations - the changing composition of the flow to the unit also has an impact on the engine's efficiency.

Dynamic simulations showed the problem the engine control unit is facing and illustrated the danger of working with average values. The dynamic simulations also showed that a steady-state model for the recirculation is not sufficient. The modelling of the microturbine can only be done correctly when the dynamic recirculation is also modeled, which is practically impossible.

Above mentioned problems indicate the need for a solution, especially for validation of simulation models against measurements.

5 Wind tunnel test with the scale model

5.1 Scale model

The T100 is installed in building Z at the VUB campus (Fig. 12, model scale 1:200). For the wind tunnel test[1], all buildings and vegetation within 300 meters distance of building Z were included in the scale model. On Fig. 12 the scaled down stack is very easy to see. Fig. 13 shows the used scale model for the wind tunnel test.

5.2 Wind tunnel test conditions

In order to obtain a representative test for the real situation, the wind speed should be chosen in a way that the following non-dimensionless numbers remain the same [22]:

$Re = \rho UL/\mu$ (1)

$Fr = U^2/gL$ (2)

$Ma = U/a$ (3)

For experiments in which the model is held stationary during data gathering, the *Re* number and *Ma* number are the significant similarity parameters. If a model experiment has the same *Re* and *Ma* numbers as the full-scale application, then the model and the full-scale flows will be dynamically similar. For this application, the vortices around the buildings are the most important ones, so the *Re* number should be kept constant. The characteristic length *L* is scaled down by a factor 200, which would request an increase in wind speed by the same factor. However the high intensity turbulence of the *ABL* and the typical, sharp shape of the buildings reduce the *Re* number's dependency. Barlow et al. [23] state that if there is no laminar flow due to high free-stream turbulence and that the shapes are so sharp that all separation locations are geometrically determined, then there will be little dependence on *Re* number. Therefore wind speeds were kept the same as in reality. For the test, the wind speed was increased from 2m/s to 12m/s. Above this wind speed, for any wind direction, no more

[1] All technical details of the creation of the Atmospheric Boundary Layer, as well as the length scale determination will be presented in an upcoming paper.

recirculation was noticed due to the good diffusion of the smoke. The same argumentation as used for setting the free wind speed is used to determine the necessary speed of the exhaust gasses and the inlet air flow. The inlet air enters the air filter with an average speed of 2.9m/s, while the hot exhaust gasses leave the stack with an average speed of 15m/s. The ventilation air's speed is a little lower, due to the lower temperature, namely 13m/s.

A smoke generator with changeable flow rate was used for the visualisation of the exhaust gasses.

5.3 Wind tunnel test results

A first short wind tunnel test was carried out at 0m/s wind speed. During this run, a problem was already revealed. As can be seen in Fig. 1, on top of the stack, a cap is placed, in order to prevent water to enter the stack. This cap disturbs the natural flow of the exhaust, forces it back down, thus enabling its recirculation into the microturbine. By removing this cap, most of the problems for 0m/s wind speed were solved. Some small recirculation remained, due to the suction at the inlet of the microturbine.

Table 2 gives the result of the wind tunnel test. A first series of tests were performed, using the scale model of the stack with the hat on top of it. Wind speed was increased for all wind direction until no recirculation remained. Results show that for many wind directions, exhaust gasses re-enters the microturbine, resulting in a lower electric efficiency of the microturbine. Especially for the wind direction South, West and South-West, recirculation is a huge problem. Even at high wind speed, the exhaust gasses still re-enters the engine. A possible explanation is the presence of the building K, which is several times higher than building Z and the stack (see Fig. 12). Building K probably produces vortices that force the exhaust air down instead of diffusing it.

Once the cap is removed from the stack, exhaust recirculation seems to solve itself for most of the wind directions. However for the wind coming from over building K, (wind direction

South, South-West and West (see Fig. 2)), recirculation remains a problem, even for high wind speeds. By making the stack 2 meters higher, the problem can almost be solved completely.

6 Conclusion

In this paper, exhaust gas recirculation has been studied on a microturbine *CHP* installation. The exhaust gas recirculation on the T100 microturbine was first noticed during experiments with steam injection in the engine. Due to the exhaust recirculation, the composition and temperature of the inlet air varied continuously. These changing inlet air conditions resulted in an unstable operation of the microturbine.

Analysis of the measured inlet temperature and the produced power showed that the unsteady regime of the microturbine was caused by changing inlet conditions.

Two sets of simulations, steady-state simulations in ASPEN® and dynamic simulation in Simulink® showed the effect of the exhaust recirculation on the overall performance of the microturbine. Steady-state simulations indicated that the loss in efficiency was caused by the exhaust gas recirculation. Not only the higher inlet air temperature, but also the changing composition of the inlet air, plays an important role in the loss in efficiency. Dynamic simulations showed the influence of the frequency and amplitude of the recirculation on the average performance. The significant influence of the exhaust recirculation on the global performance of the microturbine impedes validation of simulations against measurements. Modelling the recirculation is extremely difficult, due to the complexity of the process. In order to obtain good measurements for validating simulation models, exhaust air recirculation should be avoided in reality.

In the second part of this paper, solutions for the recirculation problem were proposed. By generating the Atmospheric Boundary Layer in an industrial wind tunnel, the exhaust recirculation could be simulated on a scale model. Wind tunnel tests visualized the recirculating problem and its dependency on wind direct and speed. Above a certain wind speed, no recirculation was observed, due to the good diffusion of the smoke in the air. The results from these wind tunnel tests will be used to make adaptations to the T100 installation and formulate certain recommendations for preventing such exhaust recirculation.

7 Future Work

Using the conclusions from the wind tunnel tests, adaptations will be made to the stack (position and height) and new measurements will be performed on the T100 in order to verify whether the problem has disappeared.

Once measurements on the T100 prove the stable operation conditions, the next step will be the full characterisation of the T100 compressor performance map in a first stage and the whole microturbine in a second stage.

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Figures

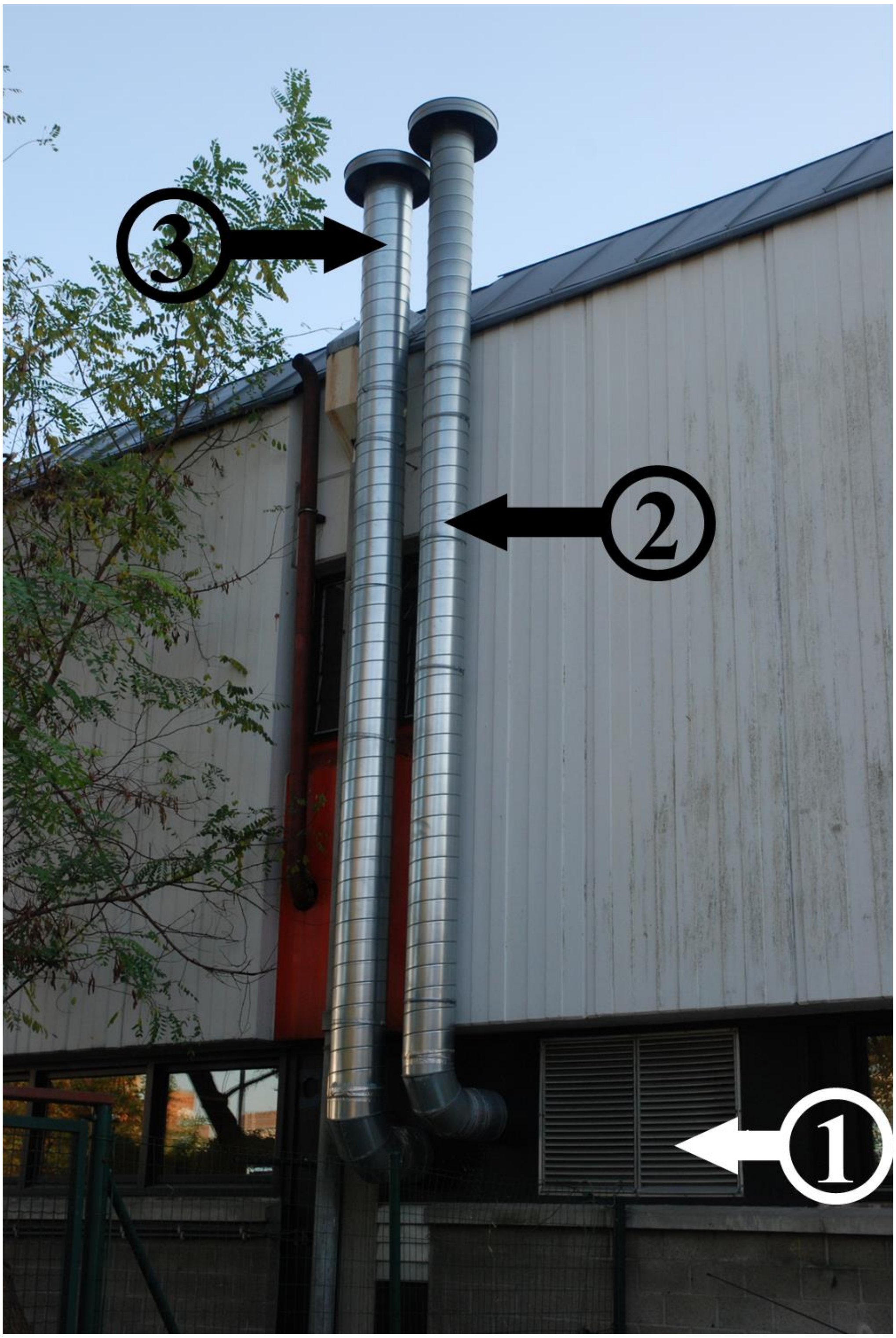

Figure 1: Air intake and both stacks of the microturbine. (1 air intake for microturbine and ventilation, 2 exhaust stack, 3 ventilation stack)

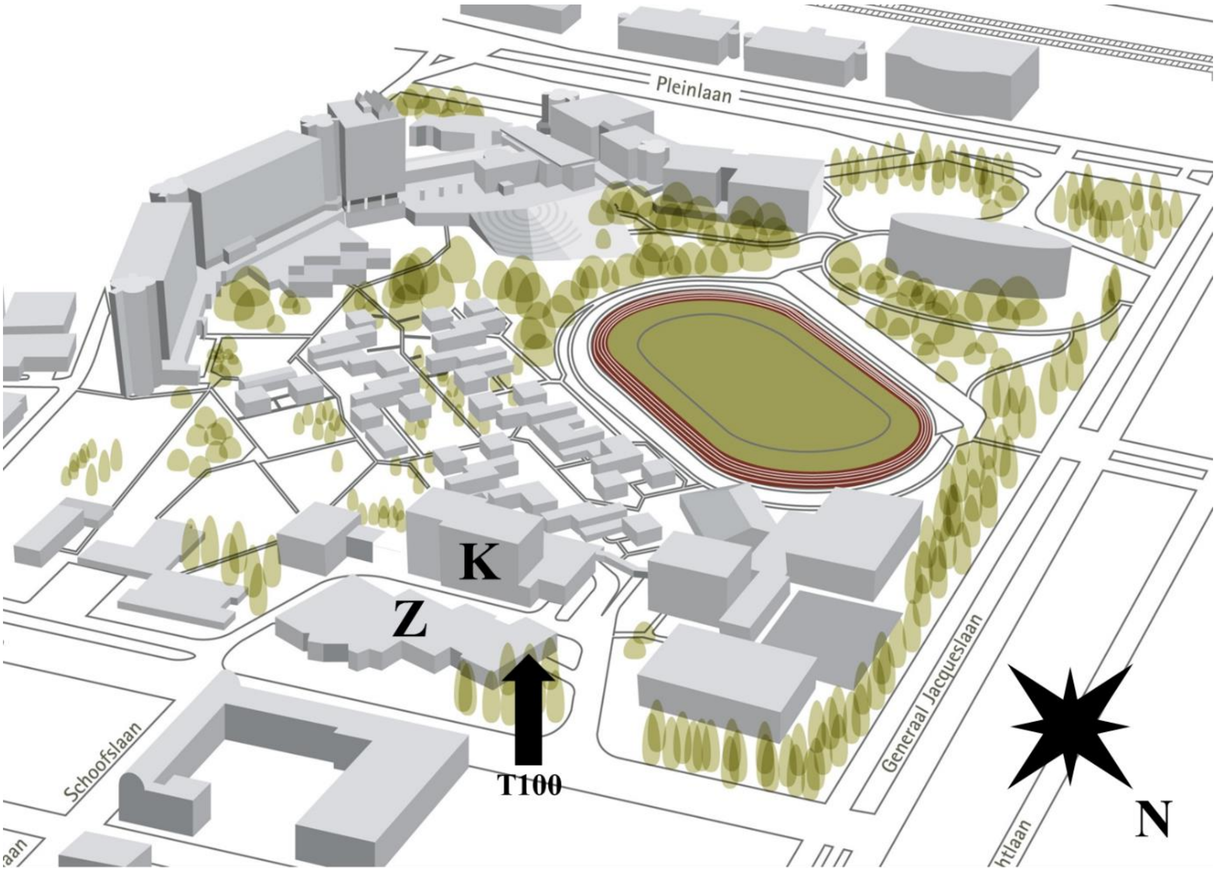

Figure 2: Surroundings of building Z, equipped with the T100 microturbine, at VUB campus.

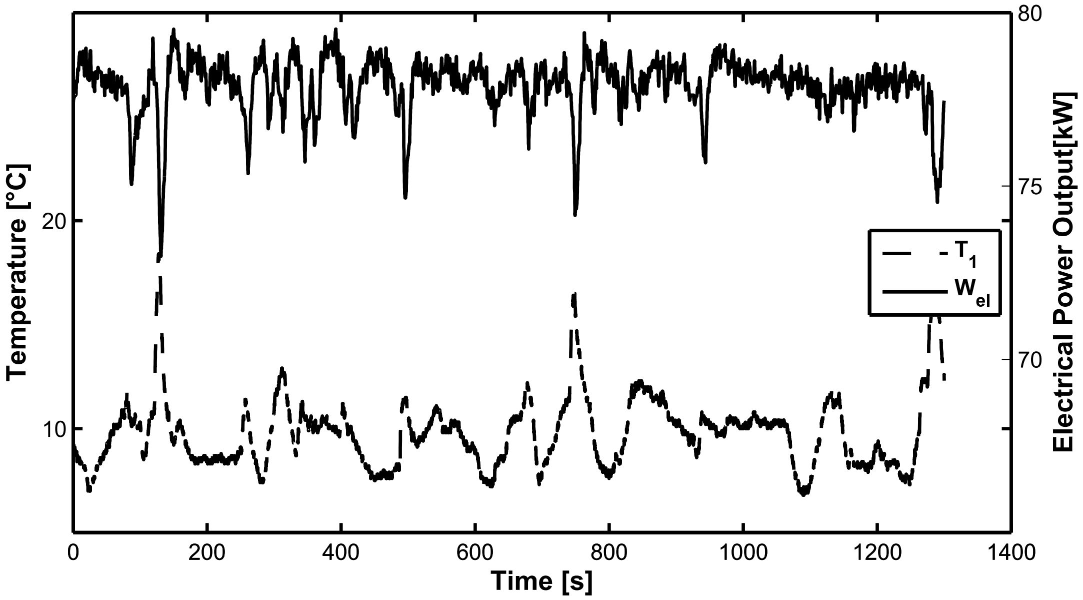

Figure 3: Changing inlet air temperature and produced electrical power output, due to exhaust gas recirculation.

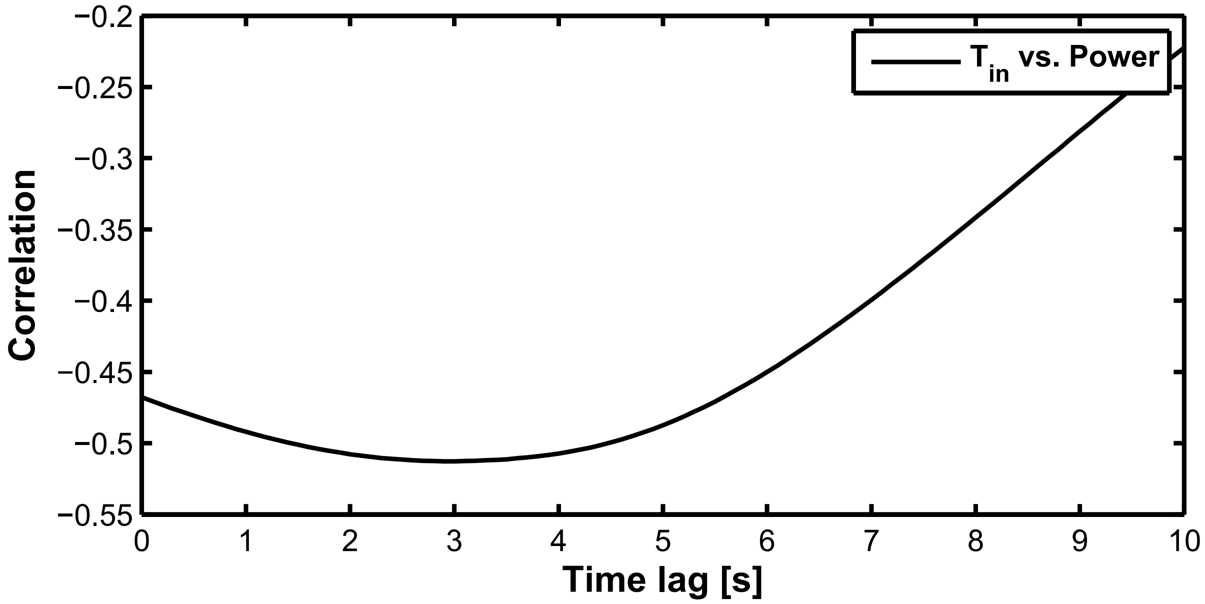

Figure 4: Correlation between inlet temperature and produced power.

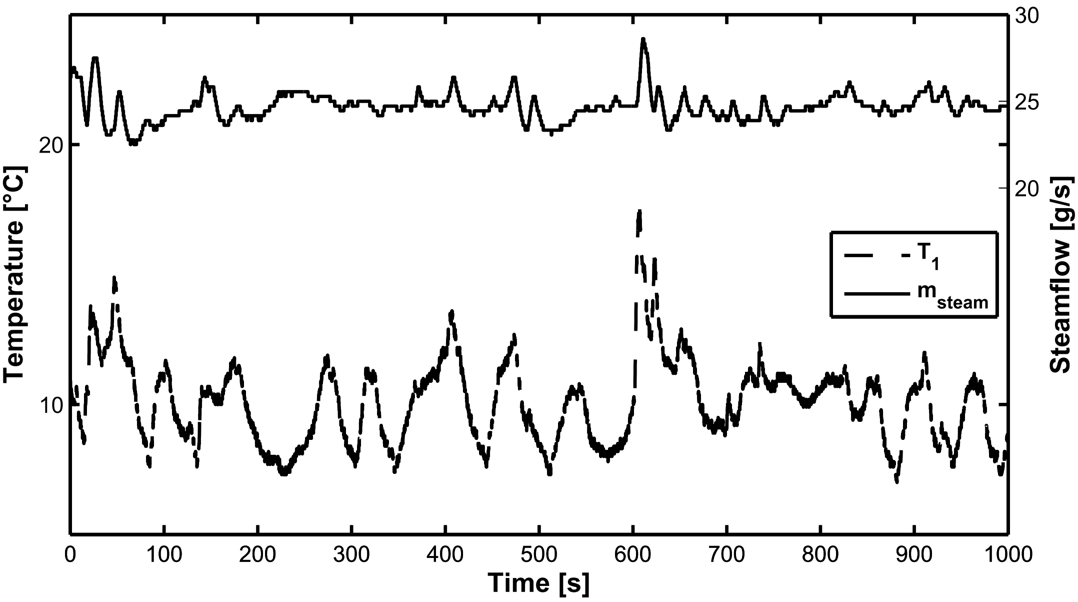

Figure 5: Changing steam flow due to changing inlet air temperature

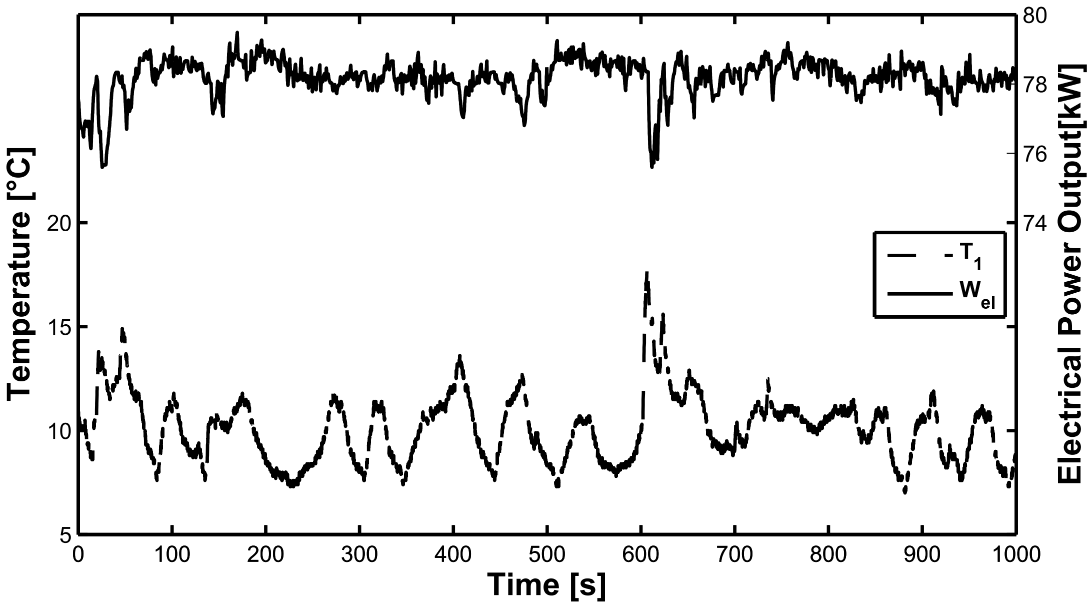

Figure 6: Inlet air temperature variations and electrical power output variations, due to exhaust gas recirculation (with steam injection).

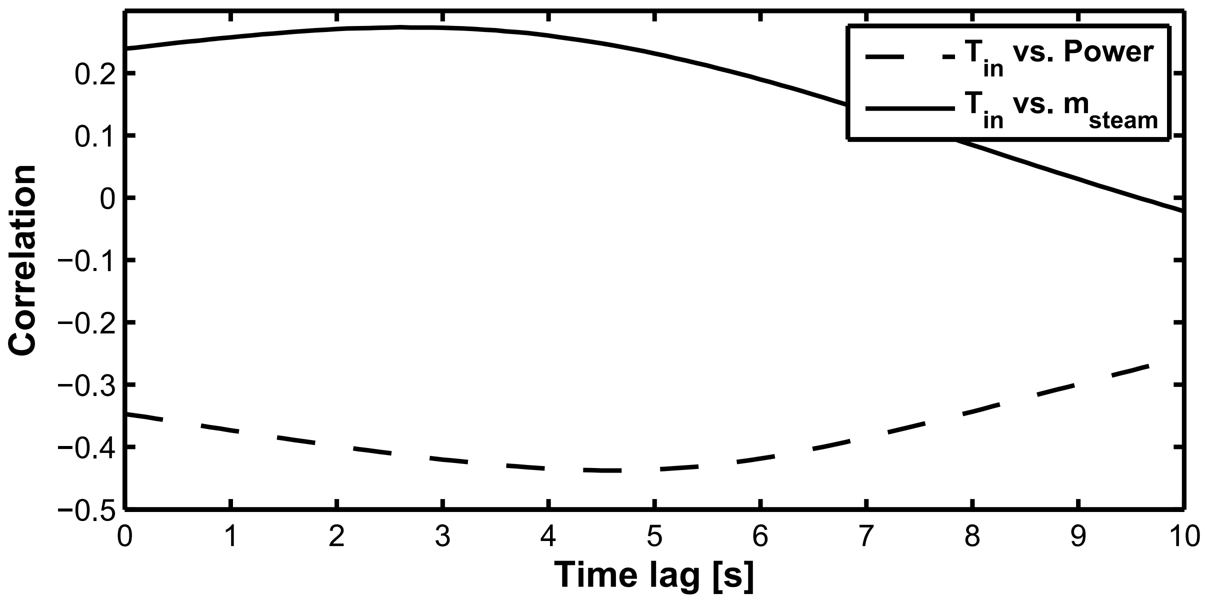

Figure 7: Correlation between inlet air temperature, electric power production and steam injection rate.

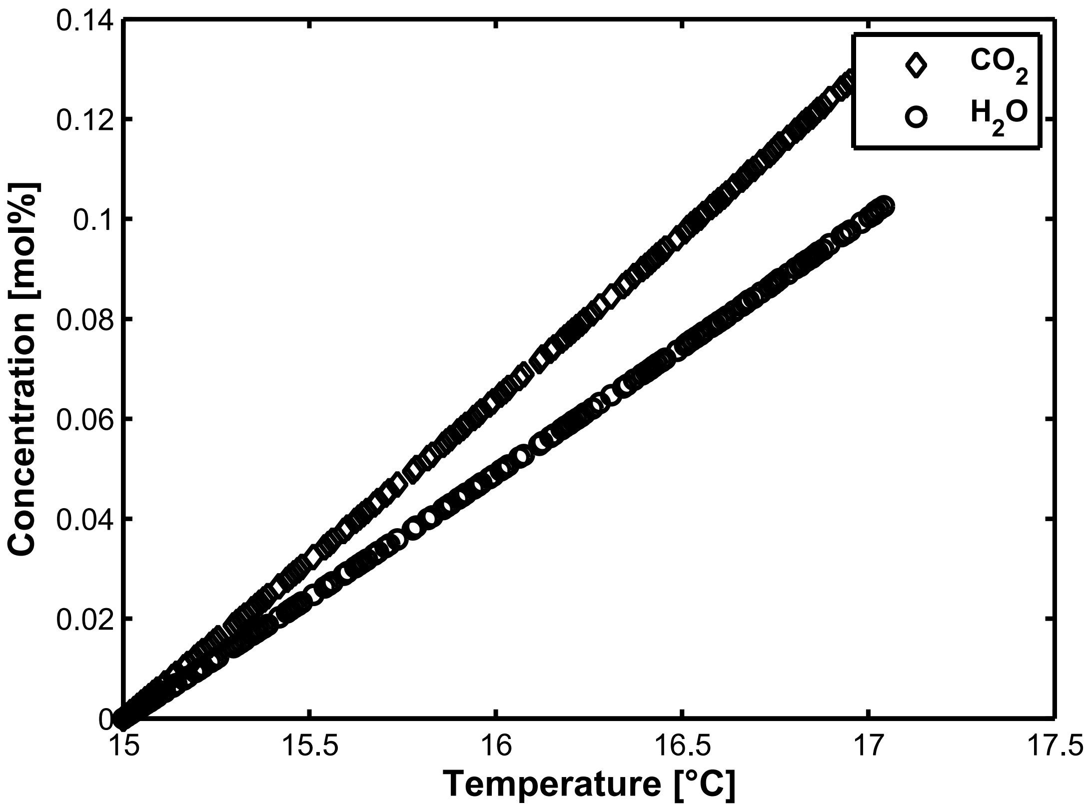

Figure 8 : Appearance of combustion product in the inlet air of the compressor, due to the rising recirculated exhaust gas partition in the inlet air of the microturbine.

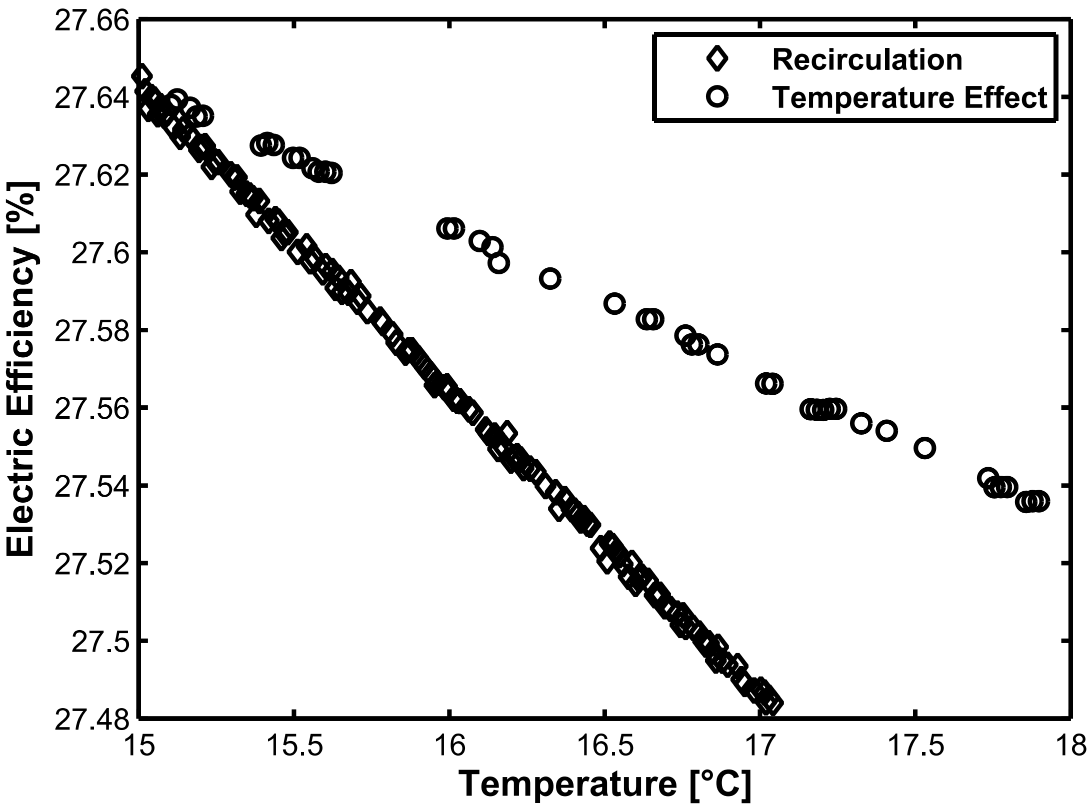

Figure 9: Influence of recirculation and changing inlet air temperature on microturbine performance. 'Recirculation' represents the results of the simulations with the exhaust gas recirculation (changing inlet air temperature and composition). 'Temperature Effect' shows the results of the simulations pointing out the effect of a rising inlet air temperature (changing inlet air temperature, but constant composition).

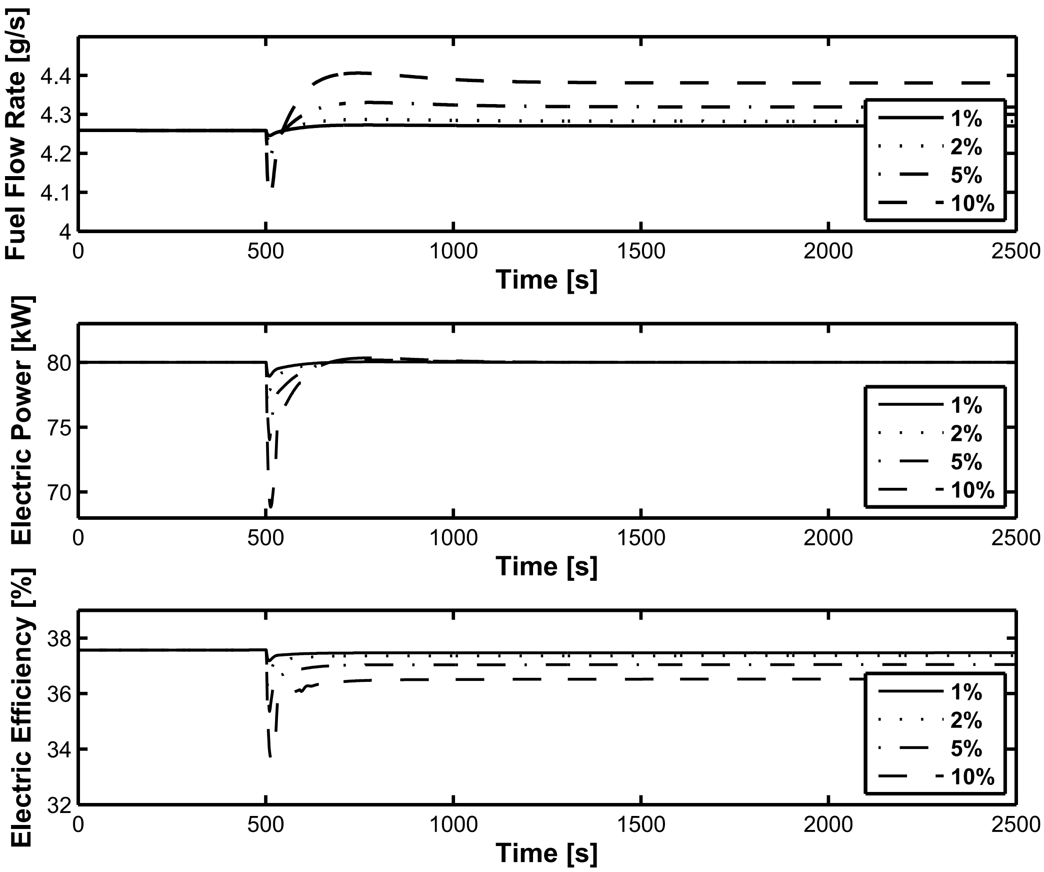

Figure 10: Step response of the fuel flow rate to the combustion chamber, the produced electric power and the electric efficiency of the T100 on a change in inlet composition.

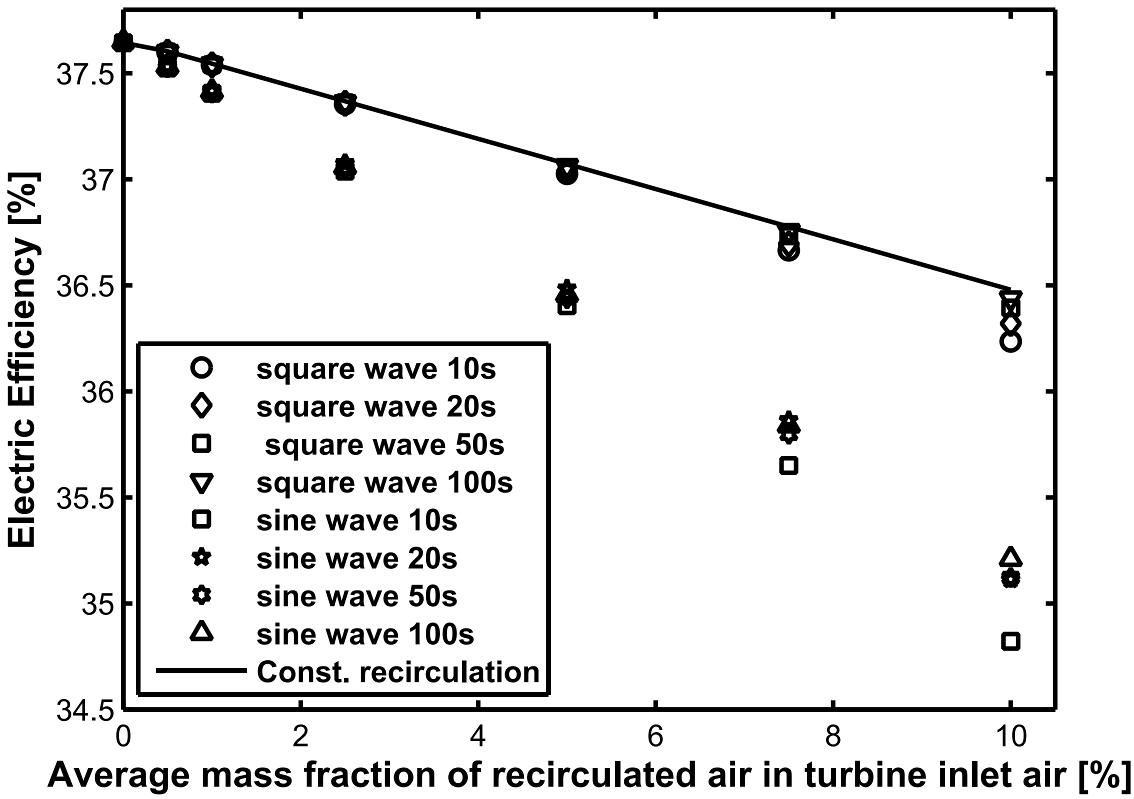

Figure 11: Results of dynamic recirculation simulations.

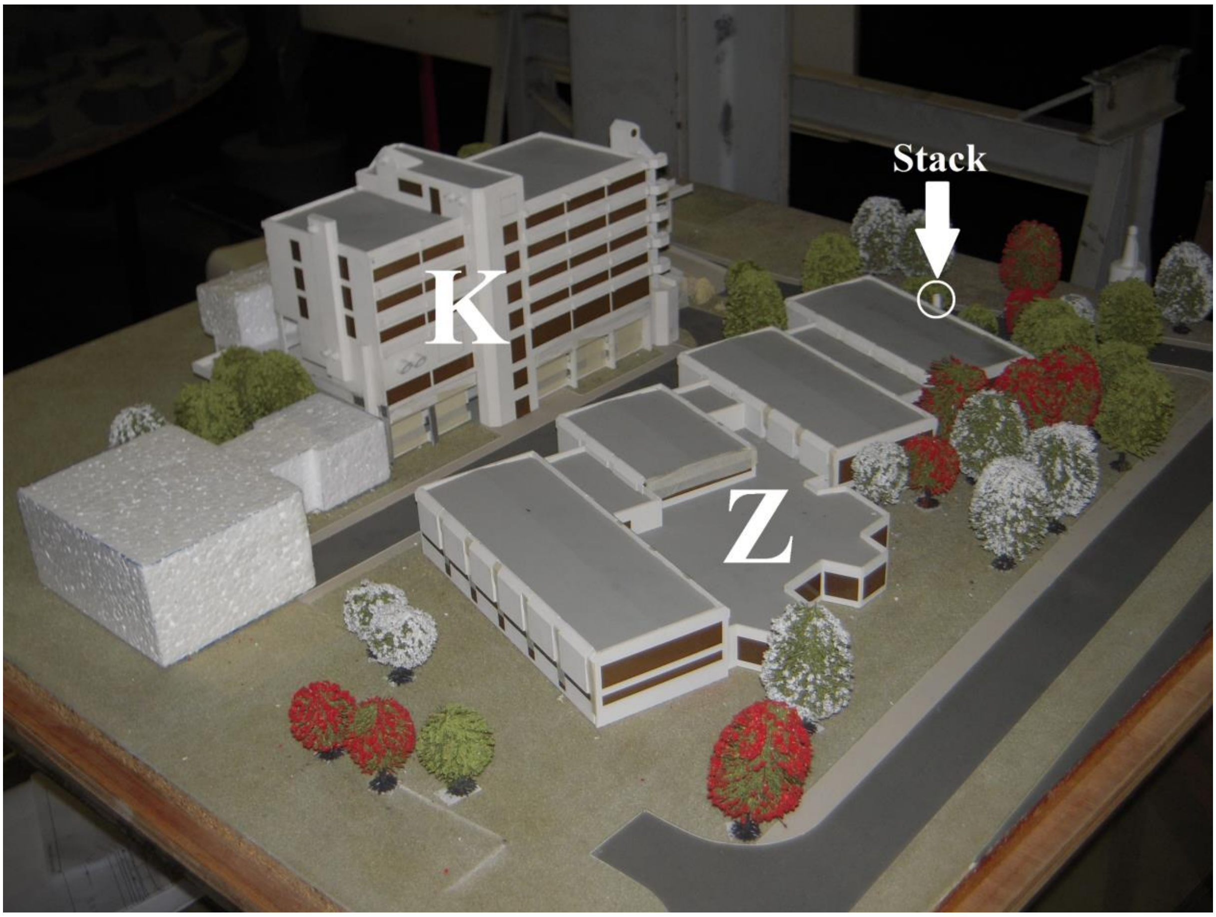

Figure 12: 1:200 scale model of buildings Z and K.

Figure 13: 1:200 scale model of building Z and surrounding

Tables

Table 1: General data about the T100 microturbine

Electric power	100 kWe
Thermal power	167 kWth
Total power consumption	333 kW
Electric efficiency	30 %
Total efficiency	80 %
Nominal speed	70,000 rpm

Table 2: Results of wind tunnel test on recirculation

Wind Direction	With cap	Without cap	Necessary extra Height
North	No recirculation	No recirculation	/
North-East	Recirculation till 4m/s	No recirculation	/
East	Recirculation till 8m/s	No recirculation	/
South-East	Recirculation till 8m/s	No recirculation	/
South	Recirculation till 8m/s	Recirculation till 8m/s	1 to 1.5 m
South-West	Recirculation till 12m/s	Recirculation till 12m/s	1 to 1.5 m
West	Recirculation till 12m/s	Recirculation till 12m/s	2 to 2.5 m
North-West	No recirculation	No recirculation	/