Experimental Investigation of the Novelty Process of Rankine Compression Gas Turbine (RCG) for an Industrial Pilot Test

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Abstract

A novel patented type of a combined cycle has been studied in the context of an industrial application. This cycle is called the Rankine Compression Gas Turbine (RCG). It consists of a combined Rankine and gas turbine cycle like the normal combined cycle but with a different layout. Its innovation is that the air compressor is driven by the steam turbine, leaving the gas turbine to act as a free power turbine. With this technology, flexible load feature is guaranteed and quick transient response time which fosters the RCG implementation in not only decentralized energy generation systems, but also mechanical drives. A 5kWe RCG add-on prototype has been installed at Houstindustrie Schijndel (HIS) which is a wood processing factory in Eindhoven, the Netherlands that has a biomass furnace and steam boiler. Some experiments have taken place while operating the RCG add-on at HIS. The RCG add-on cycle provides a rapid response transient time up to 3-4 seconds for flexible power loads for the electricity peak-shaving demand. Additionally, the economic assessment of the RCG add-on system proves its feasibility with a payback period of 3 to 5 years, depending on the scale of the industrial application.

Keywords: Novel combined cycle, Free power turbine, Add-on prototype, Rapid response, Electrical peak-shaving.

1 Introduction

Firm procedures have been taken to reduce the excessive use and dependence on fossil fuels by balancing the usage with other renewable energy resources due to the necessity of energy transition. Renewable Energy is directly affected by weather patterns which significantly affects the stability of power generation in the grid, and it is not compatible yet for electricity production in peak-shaving hours. This has led to massive investments coming from different organizations, especially governments, to fund the research and development of applicable and efficient energy transition systems. One of the main targets of this research is to reduce the consumption of fossil fuels used for energy production and seek solutions to replace that by another renewable source like biofuels. Recently, the main challenges for these technologies are not the ability to handle flexible loads, but also maintaining the grid stability. Therefore, an industrial application which can provide rapid response for power fluctuations is needed. This application can help in reducing the electricity cost from the grid [1].

That's how the concept of a new type of combined cycle was introduced to fill this gap by having a free shaft power turbine. This means that this cycle will have the ability to operate and respond rapidly at various speeds in addition to giving torque at standing still loads. This is a unique approach for a combined cycle. As a result, by introducing this new technology for the combined cycle, it will be doable to install it in applications where there were no mean to implement it before such as, mechanical drives and decentralized power systems. This innovation is called the Rankine Compression Gas Turbine cycle (RCG) [2].

In 2006, Ouwerkerk modeled [2] the RCG proof of principle using MATLAB. Further work was done regarding the techno-economic feasibility of the RCG system, and it was published in the Applied Thermal Engineering Journal. After that, there were many experimental investigations of the system to be further studied. Later, a prototype was developed at The Thermo Fluid Mechanical Engineering Lab (TFE) of Eindhoven University of Technology.

In 2009, Ouwerkerk continued [3] the development of RCG to prove the scalability of the system. A 1MWe pilot installation was designed from industrial commercial available components. It was intended for a combined heat and power application. This has proven the concept of the scalability of RCG as a stand-alone system.

In 2017, Ouwerkerk proposed a new version [4] of the RCG that can be featured as an add-on to solid fuel fired steam boilers. This version of the RCG system aims for the cogeneration concept of jointly generating hear and electricity. The electrical power ranges from 100-1000kWe with the uniqueness that the system has a flexible load ability for generating electrical power output within seconds.

In this paper, the proof of concept of the RCG as an add-on system is illustrated. A 5kWe RCG add-on has been installed and operated at Houstindustrie Schijndel (HIS) which is a wood processing factory in Eindhoven, the Netherlands that has a biomass furnace and steam boiler [5]. Additionally, there is an evaluation of the experimental results to validate the rapid response of the RCG add-on system for electrical peak-shaving loads. Finally, an assessment for the economic feasibility of the RCG add-on is investigated.

2 The RCG add-on concept

As shown in Figure 1, the proposed process scheme of the RCG add-on is presented for an existing industrial steam system [4]. Part of the resulted steam from the factory's boiler is used to run the RCG add-on cycle. The steam turbine drives the compressor. The compressed air goes through a mounted heat exchanger to the furnace. Then, it is expanded in the power turbine which is connected to an electrical generator. This way, the expansion turbine driving the generator is decoupled from the steam system. With the power control valve, the hot compressed air can be either lead through the turbine or bypassed, which allows the rapid response of the power cycle for flexible loads at electrical peak-shaving demand, while the steam flow and steam conditions are not affected. The resulted hot gases from the turbine are reinjected again to the furnace.

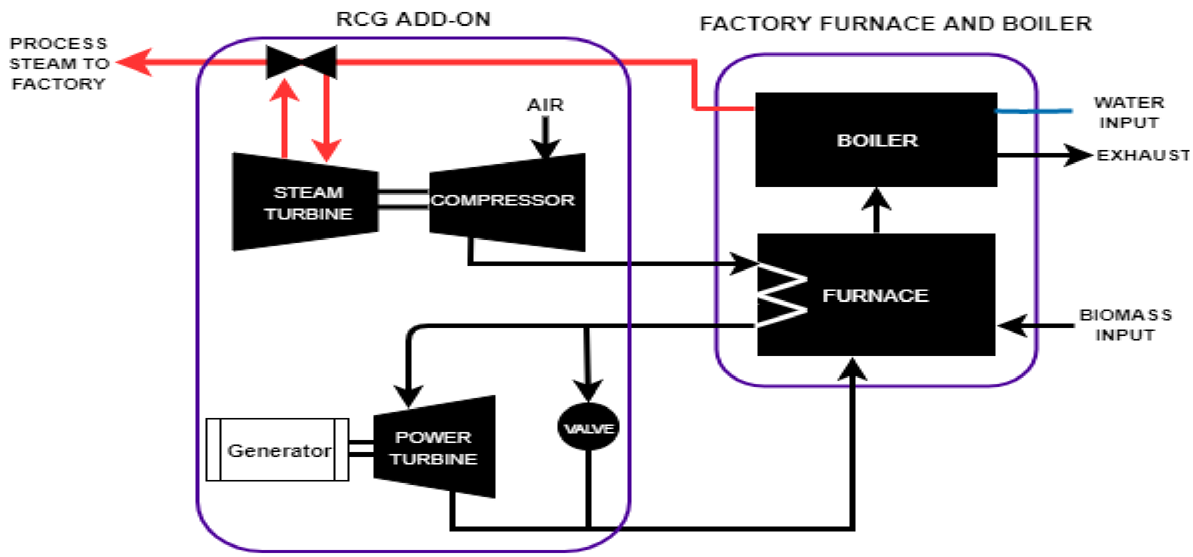

Figure 1 Process diagram of RCG add-on (patent EP1492941 and PCT/NL2017/050505) [4]

Figure 2 shows the process flow diagram of the RCG add-on at the factory. There are three lines represented in the diagram for different flows: The grey solid color represents the flow of the steam inside the RCG add-on, the dashed line represents the airflow and the solid black line shows the main steam line to the factory. The main components are a compressor (CP002), a steam turbine (ST003), a heat exchanger (HE004) and a power turbine (PT005) which is connected to a generator (GE006). The power control valves (FH120A&B) in addition to the bypass valve (BV009) play a key role in controlling the power output of the cycle in terms of load flexibility.

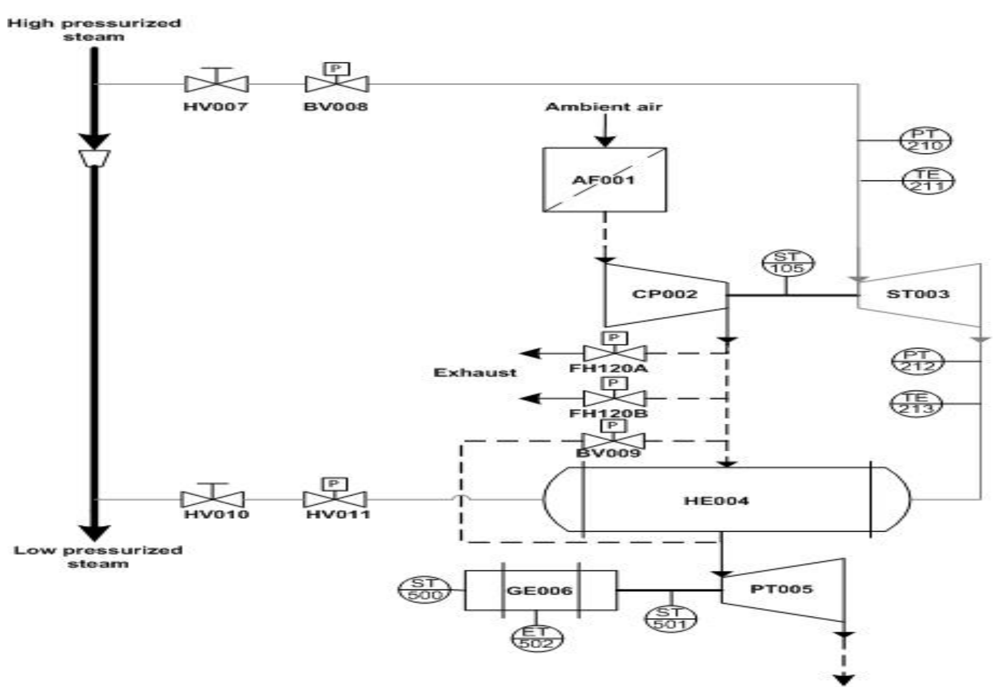

Figure 2 PFD of the RCG add-on cycle at HIS

Figure 3 shows the actual RCG add-on installation with its control panel that operates all the valves and data-acquisition.

Figure 3 The 5kWe RCG add-on at HIS factory

3 Experimental results and discussion

Experimental work for the 5kWe RCG add-on has taken place and the results are discussed in this section. The sampling time of the experiments is 1s due to the industrial environment where the RCG add-on is installed. Additionally, the resolution of the power measurements is approximately 75 W. It has been decided to divide the operation into three experiments; start-up the system, lower power variations and higher power variations for peak-shaving. As shown in Figure 4, the output power in watts is presented throughout the whole period of the operation in seconds.

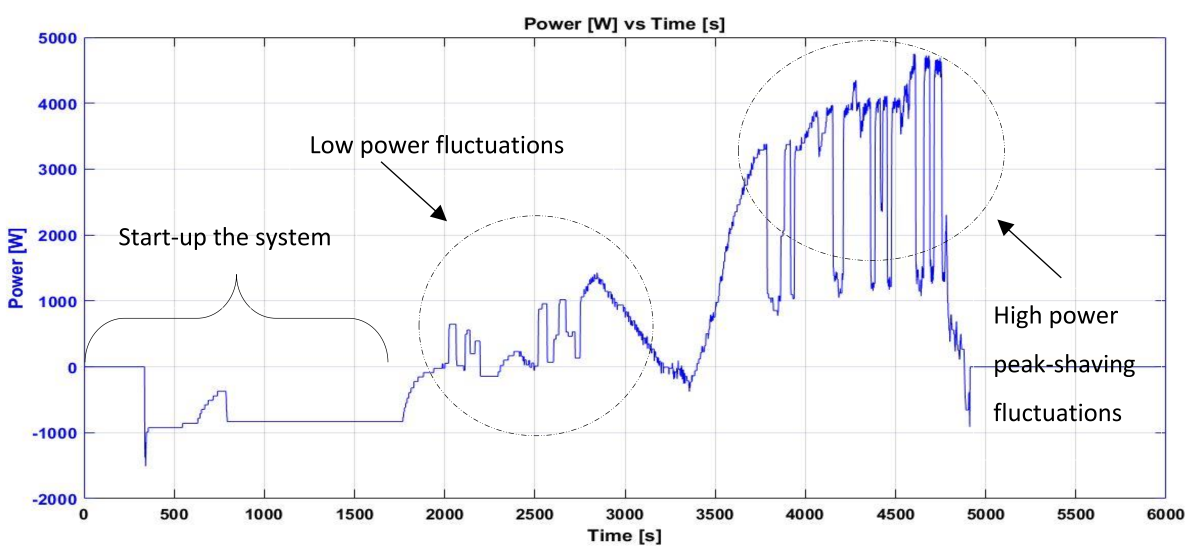

Figure 4 Overall power output of the RCG add-on cycle

In the first stage, the system is heated and taken into operation before performing the peak-shaving stages. It includes heating the pipelines for later operations and the start of the power cycle. Once the steam cycle is taken into operation, the RCG add-on is ready for the second stage where the quick responding peak-shaving concept is demonstrated for almost 22 minutes. The electrical output power ranges from 0 to 1300W, which is almost 1/3rd of the maximum power output. The fluctuations in power output are created for different time intervals to visualize the time duration to step-up from low to high power. Between the second (2000s to 2750s) and third stage (3300s to 3800s), the steam flow through the RCG add-on is increased. This allows the compressor to run at higher power and thus produce more compressed airflow. As a result, the power turbine (PT005) can be run at a higher constant speed to be ready for higher power peak-shaving fluctuations. While ramping up, the RPM of the power turbine (PT005), and generator (GE006) increase simultaneously. Additionally in the third stage, the RCG add-on is operated for power fluctuations between almost 1000W up to 4800 W for around 21 minutes. The three divided stages of operating the RCG add-on at HIS are illustrated in detail in the upcoming subsections while analyzing the results.

3.1 Lower power peak-shaving

At the start of the lower power peak-shaving stage, both power control valves are open. Therefore, there is no power output as the steam is only circulated in and out of the RCG add-on. Under these conditions, the RCG add-on is in the standby mode to respond rapidly within seconds for electrical peak-shaving demand. Figure 5 shows an interval of the power output of the lower power peak shaving and the status of the power control valves. It shows the impact on the power output while changing the settings of the air valves. The power control valve setting “0%” means fully closed, while “100%” means fully open. Whenever both valves are open, the power output is almost zero. At t=2600s, one valve is open and the other is closed and the power output is around 470W. Then by closing bother power control valves at t=2631s, the power output increases more than the double to reach around 1000W. These experiments show that the power valves can be used as power switches between approximately 0, 450 and 1000W.

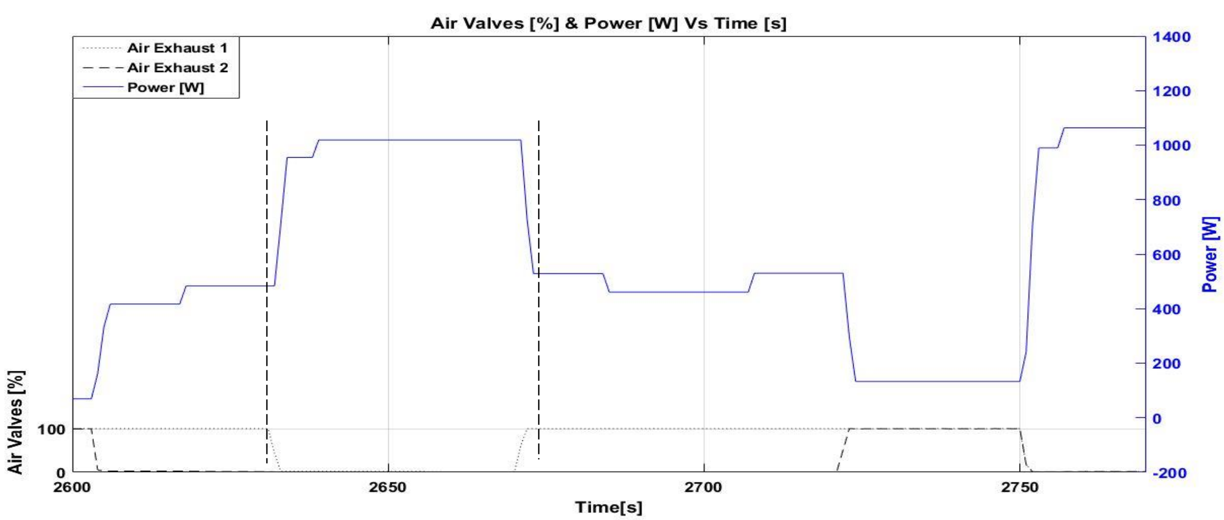

Figure 5 An interval of the lower power peak-shaving showing the relation between the power output and the change of power valves’ settings

To show that the steam which is reinjected into the steam main is not influenced by the power valve settings, the pressure and temperature of the outlet steam are shown in Figure 6 during the same time interval as shown in Figure 5. The steam pressure along the whole time interval is 1.35±0.01 bar at a constant temperature of 109±1°C. Therefore, the steam leaving the RCG add-on is saturated at a constant pressure.

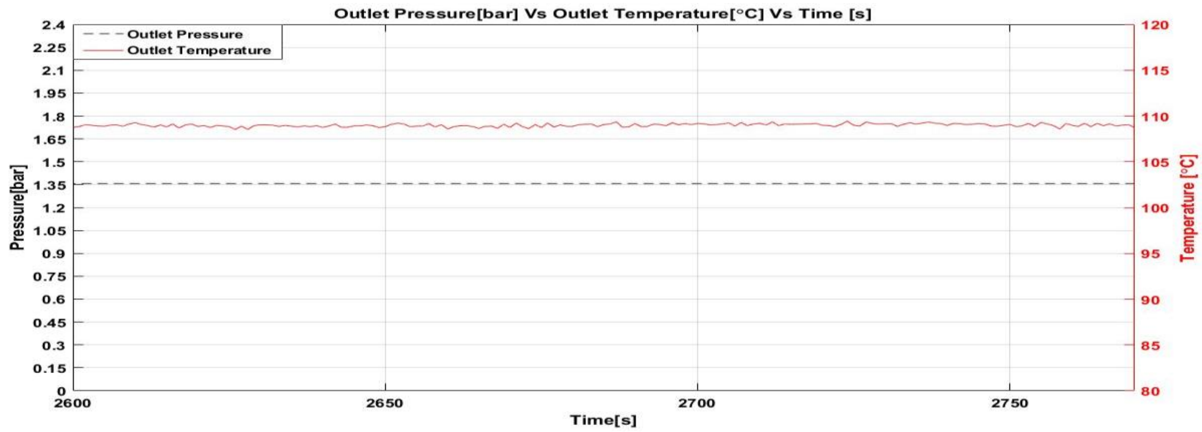

Figure 6 The outlet temperature and pressure of steam for the lower power peak-shaving interval

For a better illustration of the time response of the RCG add-on, a smaller time interval (2625s-2680s) is shown in Figures 7 and 8. Figure 7 demonstrates that the time difference between giving the command through the control panel to close the power control valves and the actual closing is 2s (2631s-2633s). This means that the used power valves have a response time of about 2s. Additionally, the time between the full closure of the power control valves (t=2633s) and attaining the full-load power output at t=2634s is 1s.

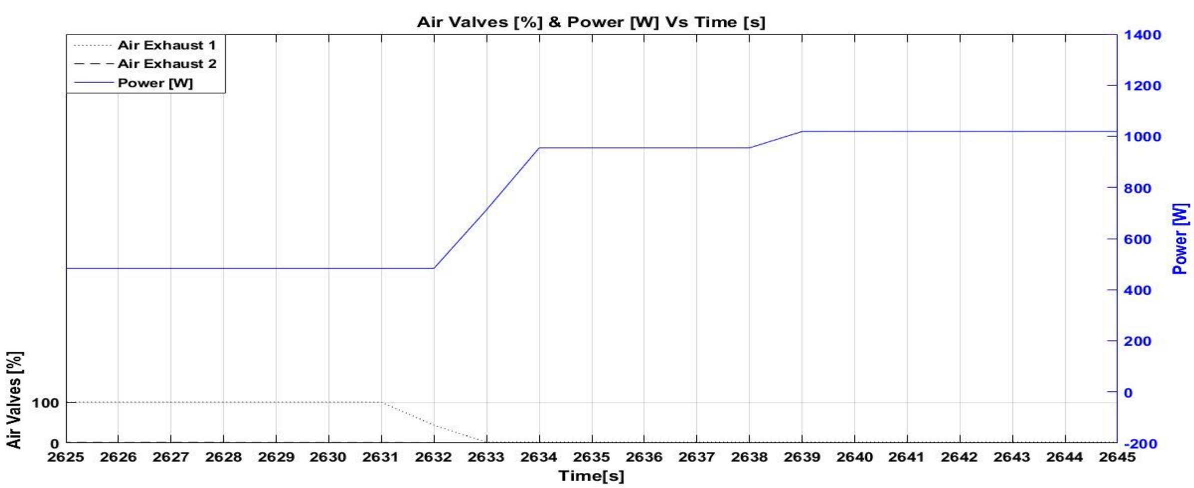

Figure 7 A chosen time interval (2625s-2645s) while closing both air valves for lower power peak-shaving

After reaching the full-load power of 1000W at the interval (2625s-2645s), one of the control valves is opened again as shown in Figure 8 to attain a part-load power of 500W. This shows the same time of 2s (2670s-2672s) between giving a command to open the power control valves and the actual opening. The time to reach zero power after the full opening of the valves is 1s (2672s-2673s). Therefore, Figures 7 and

8 show that, both for step-up and step-down power settings, the time from the start of a change in power valve setting until the reach of full power is 3s.

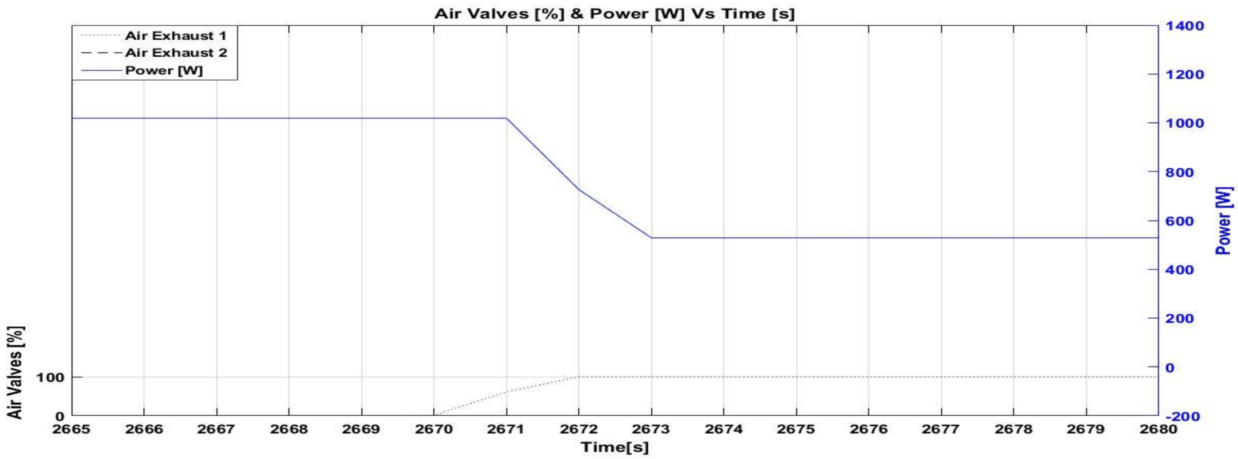

Figure 8 A chosen time interval (2665s-2680s) while opening one air valve for lower power peak-shaving

3.2 Higher power peak-shaving

After the lower power peak-shaving stage, the RCG add-on is up-scaled to a higher power peak shaving stage. As illustrated in Figure 9, the power output fluctuates along with the time interval in seconds and this shows the impact of altering the settings of the power valves. The power fluctuations in this stage are targeting almost the maximum power output of the RCG add-on. This confirms the results from the previous stage for the rapid response timing for higher peak-shaving demand. Although they are slightly less constant than at the lower power setting, the power valves now act as switches between 1300 and 4500W.

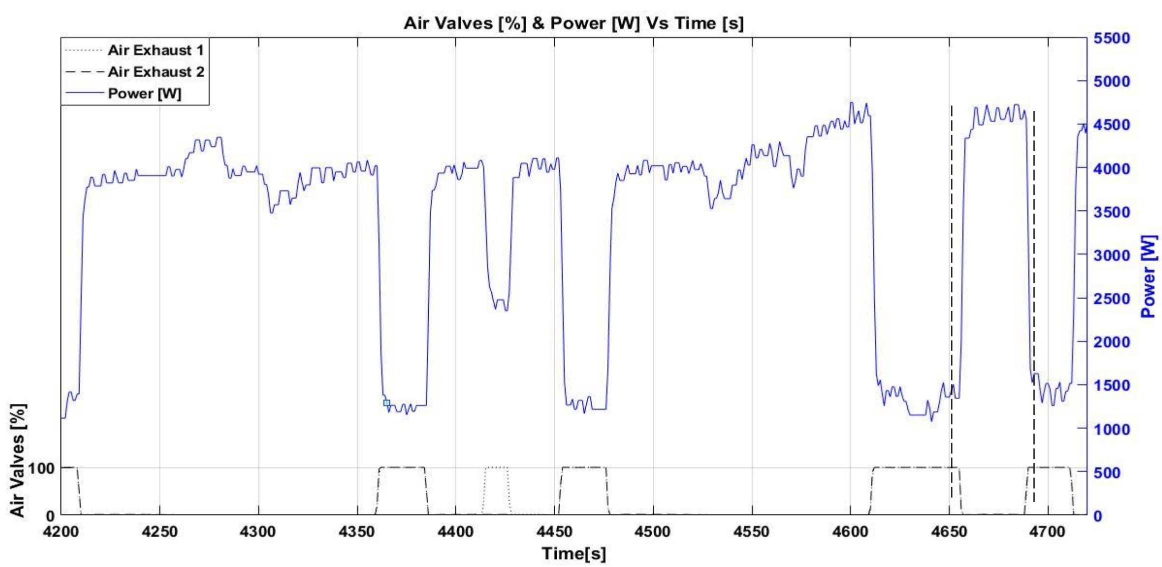

Figure 9 The relation between the power output and the change of exhaust air valves' settings in terms of time response at the High peak-shaving stage.

Figure 10 shows that the outlet steam pressure and temperature are almost constant during the whole duration and they satisfy the constant steam outlet pressure and temperature to the factory.

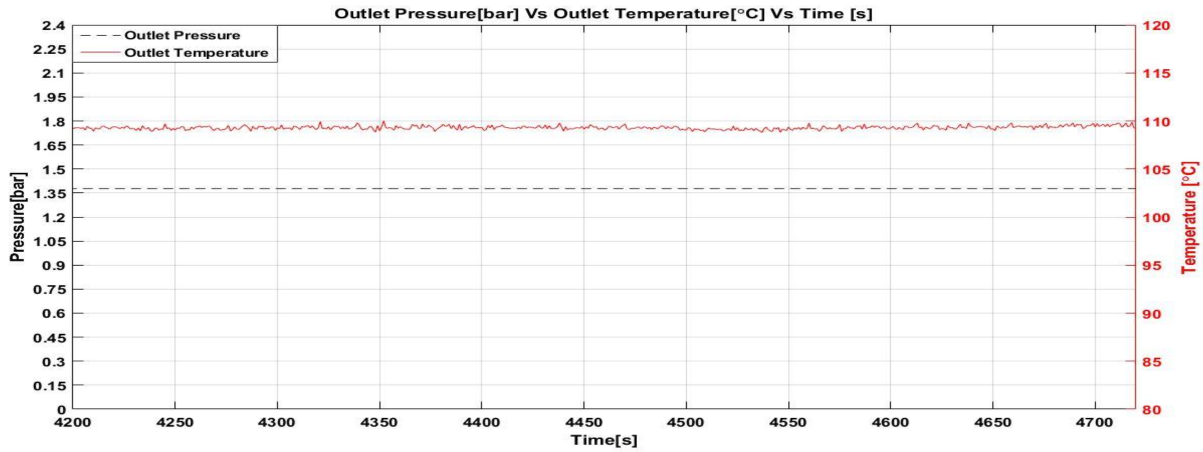

Figure 10 The outlet Steam pressure and temperature for the higher power peak-shaving stage

Figures 11 and 12 show a close up of the power transients. As shown in Figure 12, the power ramps up from around 1300W to 4500W. Both power valves were open at the beginning, then the command is given to close them at t=4655s and they are fully closed in almost 2 seconds at t=4657s. The power peak point of 4500W is achieved at t=4658s which shows that the time difference between peak power point and valves closure is around 2s. The total transient time difference is now approximately 4s, about 1s more than the chosen interval for the lower peak-shaving stage, while the power control valves take the same amount of time of 2s to fully close after giving the command through the control panel. As shown in Figure 12, the power vales are opened to regain the power output to the part load of around 1300W. The transient time duration is 2s for lowering the full-load power from around 4500W to the 1300W. Additionally, the opening time duration of the valves is 2s (4688s-4690s) which validates the same time response that is obtained in the lower power peak-shaving stage.

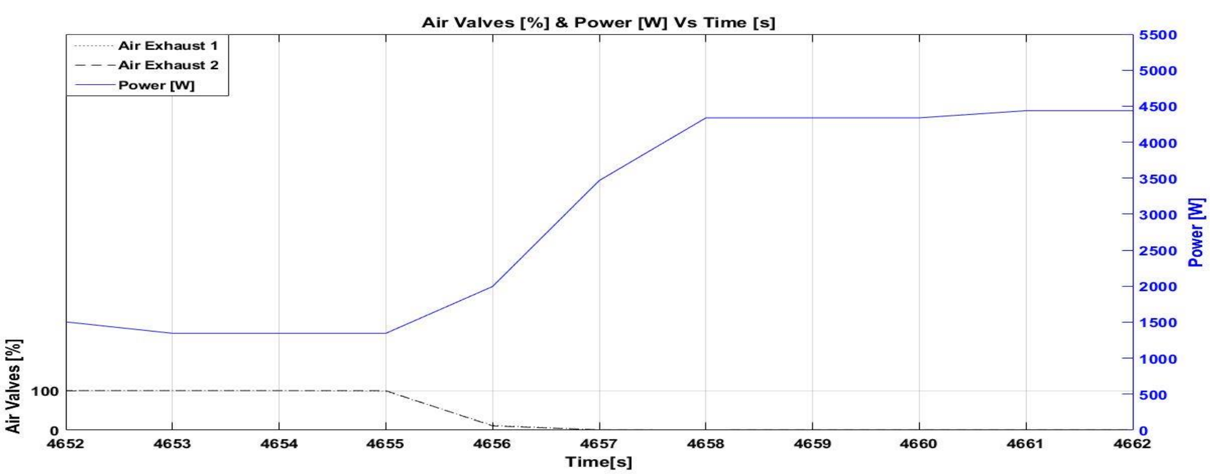

Figure 11 A chosen time interval (4652s-4662s) while closing both air valves for higher power peak-shaving

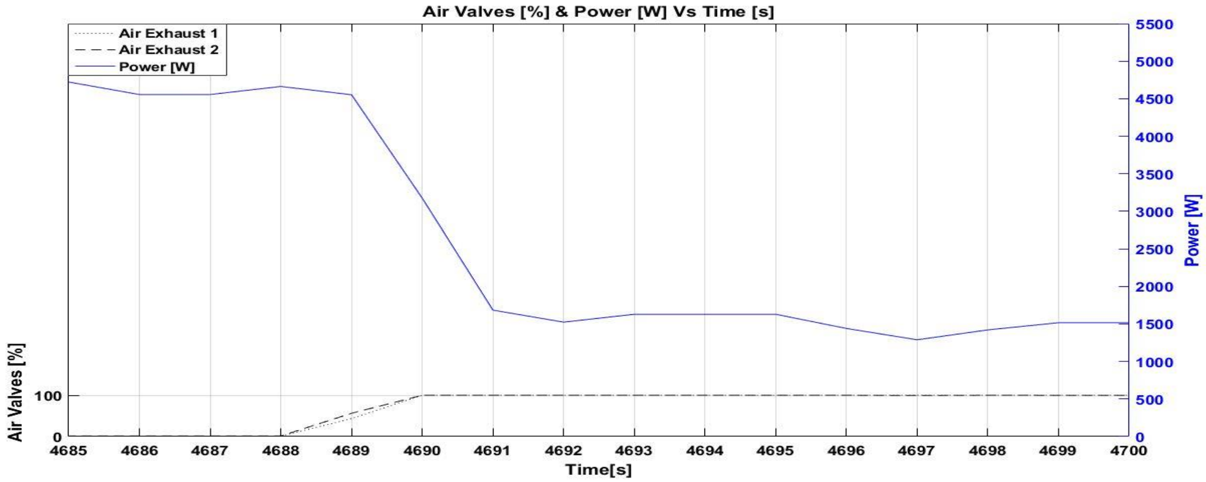

Figure 12 A chosen time interval (4685s-4700s) while opening both air valves for higher power peak-shaving

4 Feasibility study

For the feasibility assessment of the RCG add-on commercial system, some economic parameters are considered for the analysis such as the internal rate of return, net present value, and payback time…etc. The following equations are used for the economic assessment and the results are shown in Table 1:

$$Payback\ period, years = \frac{Investment}{Net\ annual\ cash\ flow} \tag{1}$$

$$NPV = -CAPEX + \sum_{t=1}^{n} \frac{(net\ cash\ flow)_t}{(1+i)^t} \tag{2}$$

$$0 = -CAPEX + \sum_{t=1}^{n} \frac{(net\ cash\ flow)_t}{(1+i)^t} \tag{3}$$

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{(Fuel\ and\ Maintenace\ cost)_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{(Energy\ produced)_t}{(1+i)^t}} \tag{4}$$

Where n is the specific given period of the project in years and i is the discounted rate annually.

Table 1 The feasibility analysis of the RCG add-on

	120kWe Scenario	**240kWe Scenario**	**360kWe Scenario**
Payback period	4.4 years	3.4 years	3 years
NPV	€598,000	€1,392,000	€2,191,000

IRR	22.1 %	28.6 %	32.2%
LCOE	€0.092/kWh	€0.081/kWh	€0.075/kWh

It is concluded that the RCG add-on is a feasible solution for many industries with a payback period of up to 4.4 years, depending on the type of each scenario. This time the payback period can be adequate for many industries. Moreover, the IRR indicates that the RCG add-on is a desirable and attractive solution.

5 Conclusions

The proof of the concept of the RCG add-on has been proven as an industrial application for industries where a steam boiler exists. The 5kWe RCG add-on has been implemented at HoutIndustrie Schijnel (HIS), and it is successfully operating. The experimentally obtained results prove the principle of the RCG add-on installment to provide a free power turbine which is capable of handling flexible electrical loads in rapid time response, especially during the peak-shaving demand. The time response of the RCG add-on is within 3-4 seconds, depending on the needed power output. The time response can be further improved by installing faster valves or decreasing heat-exchanger and piping volume, whenever needed for other applications. Additionally, a feasibility study has been analyzed for the commercial scale of the RCG add-on for three different scenarios: 120kWe, 240kWe, and 360KWe. The payback period is from 3 to 5 years, depending on the chosen scenario and the industrial application.

6 References

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