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.

The work aims to experimentally realize the RCG add-on working concept in industries where a steam generation system exists. A 5kWe RCG add-on prototype has been designed with the assessment of its components. Then, it 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 experimental results have been analyzed and discussed. 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.

Resumo

Nesta tese, foi estudada uma nova patente de ciclo combinado no contexto de uma aplicação industrial. Trata-se do Ciclo de Rankine de turbina de compressão a gás (RCG). Consiste numa combinação dos ciclos de Rankine e de turbina a gás como o ciclo combinado usual, mas com uma disposição diferente. A inovação consiste em que o compressor seja alimentado pela turbina a vapor, deixando a turbina a gás como turbina livre. Com esta tecnologia, fica assegurada a capacidade de produção flexível e uma de resposta transiente rápida, o que promove a sua implementação não só em sistemas descentralizados de produção de energia como também em cargas mecânicas.

O objetivo da tese é implementar experimentalmente um protótipo de RCG complementar em indústrias em que esteja instalado um ciclo de geração a vapor. Foi desenvolvido um protótipo de RCG complementar de 5 kWe bem como a avaliação dos seus componentes. No seguimento o protótipo foi instalado na fábrica Houstindustrie Schijndel (HIS), uma fábrica de processamento de madeira em Eindhoven, Países Baixos, onde estão instaladas uma fornalha a biomassa e uma caldeira a vapor.

Os resultados experimentais foram analisados e discutidos. O sistema RCG complementar garante uma resposta transiente rápida até 3-4 segundos para cargas energéticas flexíveis para dar resposta á necessidade de nivelamento de energia elétrica. Adicionalmente, foi estudada uma análise económica do sistema RCG complementar para provar a sua viabilidade com um período de retorno de 3 a 5 anos, dependente da escala da aplicação industrial.

Palavras-chave: Novo ciclo combinado, turbina livre, protótipo complementar, resposta rápida, nivelamento elétrico

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Abbreviations

RCG	Rankine Compression Gas Turbine
CHP	Combined Heat and Power
CAPEX	Capital expenditure
OPEX	Operating expense
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
NPV	Net present value
IRENA	International Renewable Energy Agency
HIS	HOUTINDUSTRIE SCHIJNDEL
EU	European Union
TU/e	Eindhoven University of Technology
C	Compressor
T	Power turbine
ST	Steam turbine
L	Loads
G	Generator
SMEs	Small and medium-sized enterprises
TRL	Technology Readiness Levels
RPM	Revolutions per minute
DN	Diameter nominal

1 Background

Heat Power BV has the patent of a novel type of combined cycle called the Rankine Compression Gas Turbine system (RCG), and it is in the phase of commercializing that technology for providing rapid response within seconds for electrical peak-shaving industrial applications where steam generation system exists.

This section provides information about the steam systems in addition to industrial cogeneration systems. It is followed by the explanation of the objectives of the thesis and the RCG concept.

1.1 Introduction

Global warming is rising at an alarming rate threating the existence of humankind and all types of species. Thus, firm procedures should be 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. Although it is clear that renewables are a cleaner and more sustainable option compared to fossil fuels, some of them are 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. Thus, it is not realistic at present to depend totally on renewable resources such as, become solar cells, wind turbines, hydropower, biofuels, tidal, energy storage, and others. 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. As a result, hybrid energy systems, which combine the usage of renewable resources and conventional power systems, can be the core of the energy transition [28].

There are various systems that can be stated as on-demand sustainable power sources which can supply on-demand electricity from a sustainable source such as batteries, diesel or gas engines and steam turbine cycles [29].

Wind and solar PV power can be stored in batteries. With a response time smaller than a second, batteries can be the fastest option for fulfilling peak-shaving demand and grid balancing. However, the flexibility for power fluctuations in addition to the capital cost should be taken into consideration [30]. That’s why an alternative solution for solid biofuels-fired steam systems can be studied to offer a rapid response within seconds.

There is a top share of the world's energy consumption in many industries which is used in the form of thermal energy. This heat is usually generated through the use of boiler and then having a resulted steam. Usually in such industries, a cogeneration system is installed for better economic and environmental perspectives. These different systems are explained in detail in the coming sub-sections [7].

1.1.1 Steam systems

Around 35 % of the world's energy consumption coming from the industrial sector [1]. This energy is being used in different forms in order to meet the sector's demand. Mainly, it is used for heat processing and electricity generation, which considered to be the most significant portion of energy consumption in this sector. The processed heat ranges from around 46% to 65% of the total industrial demand due to its importance in many industrial processes such as extrusion, drying, and distillation [2].

The industrial process heat is divided into direct and indirect heating. First, direct heating results from the combustion of fuel and has direct contact with the produced material. Second, indirect heating is the transformation of heat from another source to the material through different mechanisms such as radiation, convection, and conduction. An example of indirect heating is the generation of steam or hot water to be used for industries such as food processing and wood drying and textiles. These industries rely on a great extent on their steam production systems in order to have the required heat demand [1].

One of the current technologies to produce steam is the use of a furnace to combust fuel while having water tubes passing through the produced hot gases to generate steam [3]. The heat transfer is happening through convection. The components of a vertical boiler are shown in Figure 1. The process starts with water passing through the economizer then it is transformed later into saturated steam because of the heat transfer from hot gases. Furthermore, the steam is superheated to be ready for usage. The furnace is compatible with multi-fuel such as biomass and waste.

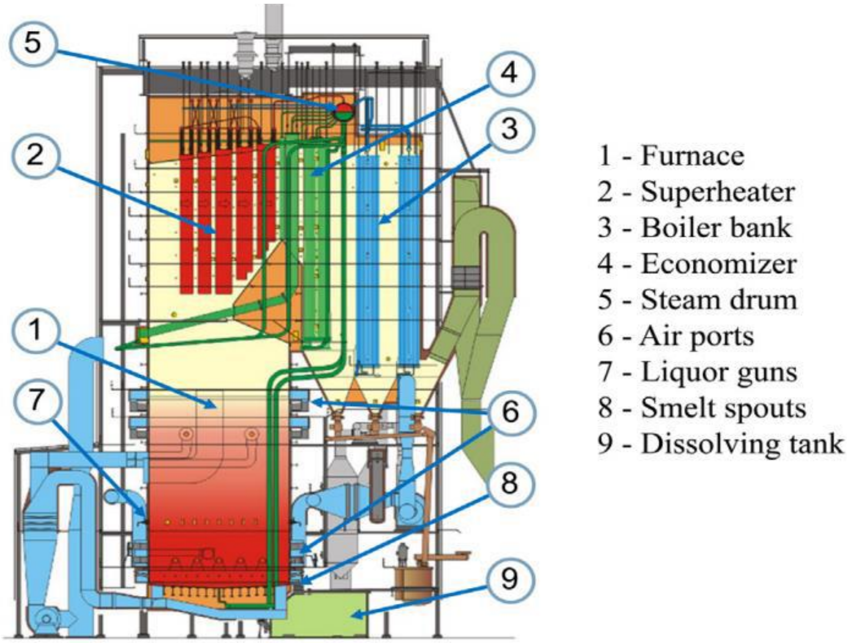


Figure 1 Vertical Boiler [3]

The produced steam pressure has to be regulated so that it is used for the required application. This is done by an expansion pressure valve or sometimes by reducing the steam temperature through the cooling system. The stand-alone steam systems have been used for a long time. However, such systems are wasting a considerable amount of energy that can be used for other purposes. For example, a steam turbine could be installed to make use of the pressure difference in order to generate power. This solution is only feasible for high power production. Moreover, the steam supply should always be consistent without any disturbance.

For various power stations around the world, the normal steam cycle is commonly used for electricity baseload energy production by the use of the generated thermal energy from burning different fuels. Moreover, they have a long lifetime working period which reaches up to 35 years. As seen in Figure 2, the steam is produced in the boiler then transferred to the steam turbine which is generally connected to a generator for producing electricity. The remaining steam after the turbine process is cooled in the condenser resulting in water which is fed back again into the boiler by a pump and the cycle repeated.

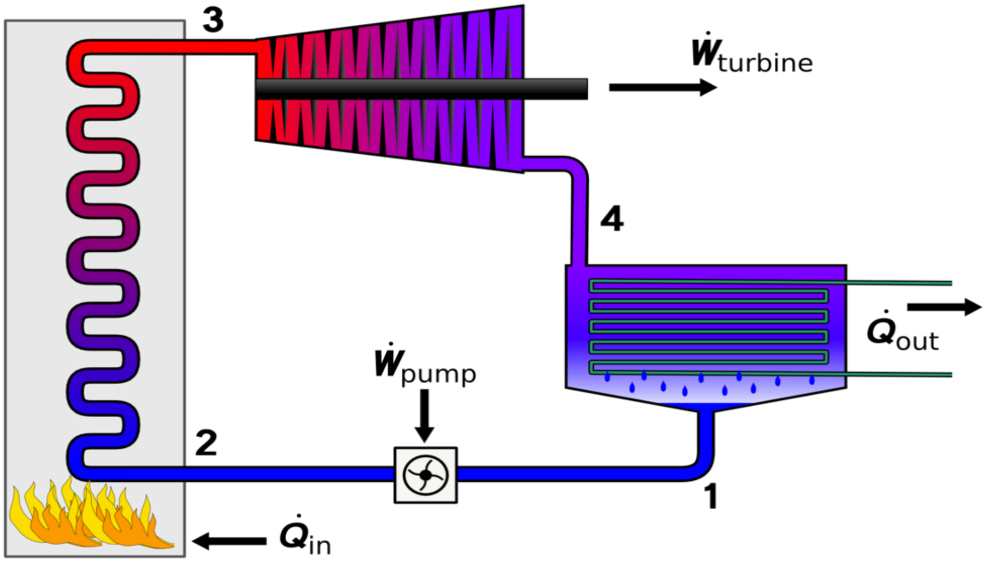


Figure 2 Physical layout of the Rankine cycle [5]

1.1.2 Cogeneration

The concept of cogeneration is to combine heat and power (CHP) engine in the same system in order to simultaneously produce useful heat and electricity at the same time. The application of cogeneration became a relevant solution in the industrial sector to use the waste heat from the steam systems. Nowadays, many facilities make use of such technology to produce their local heat needs in addition to electricity. This has environmental, economic, and technical benefits. CHP systems are more efficient in a way that they use less fuel compared to conventional systems. Moreover, the simultaneously produce thermal energy and electricity. There are different ways to measure the efficiency of the CHP system. It can be either by measuring the higher heating value (HHV) or the lower heating value (LHV). The condensed heat of the water vapor of the products is included in the HHV calculation. Thanks to the high efficiency of the system, a recognizable amount of the energy bills is decreased [4].

Figure 3 shows the difference between the CHP system and the conventional separate heat and power system in terms of efficiency. CHP system only requires 75 % of the primary energy that the separate heat and power system requires. This concludes that CHP utilize less fuel for the same output than the conventional heat and power system. This will also result in fewer pollution emissions [4].

It is shown that the conventional heat and power system uses a 147 units of fuel, 56 units for the boiler and 91 units for the power station. The calculated overall efficiency of this system is 51 %. On the other hand, the CHP system is consuming only 100 units of fuel to produce the same output of 75 units of useful energy as the conventional heat and power system. As a result, the CHP system has a better efficiency of 75 %[4].

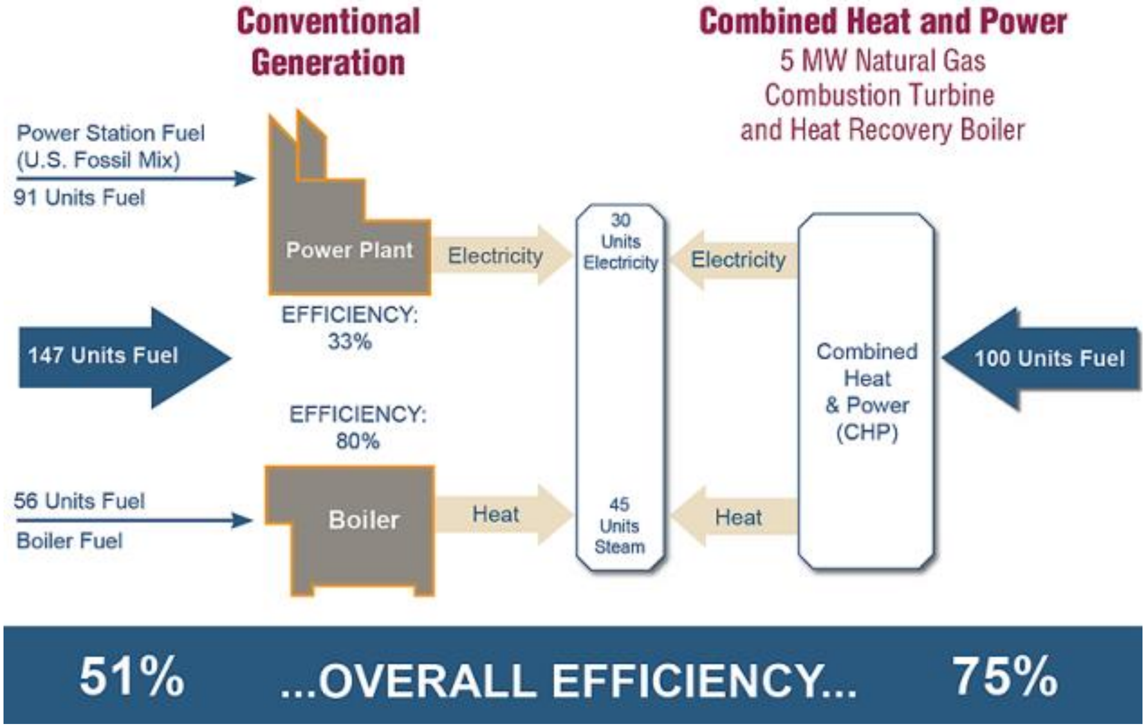


Figure 3 Efficiency comparison of CHP versus heat and power system [4]

Typically, steam turbines produce electricity with the use of the main product which is steam generation. On the contrary, another CHP systems that include a gas turbine with a heat recovery unit produces heat as a byproduct of electricity generation [4]. Table 1 shows the difference between both CHP systems in terms of advantages and disadvantages.

Table 1 Tthe advantages and disadvantages of the CHP system either with steam or gas turbine

CHP system	Advantages	Disadvantages	Available sizes
Steam turbine	• High overall efficiency • Can be installed for boilers firing various solid or liquid fuels • High durability and working life	• Slow startup • Requires a steam source	• 60 kW to several hundred of MW
Gas turbine	• High reliability • Lower emissions • No cooling required	• Low efficiency at low loading • Requires high pressurized gas	• 500 Kw to 350 MW

As shown in Figure 4, it illustrates the process of using a CHP system with a steam turbine base to produce heat and power for a facility. This can be used in many industrial processes where solid fuels such as biomass or coal are available in order to be used to fuel the boiling process.

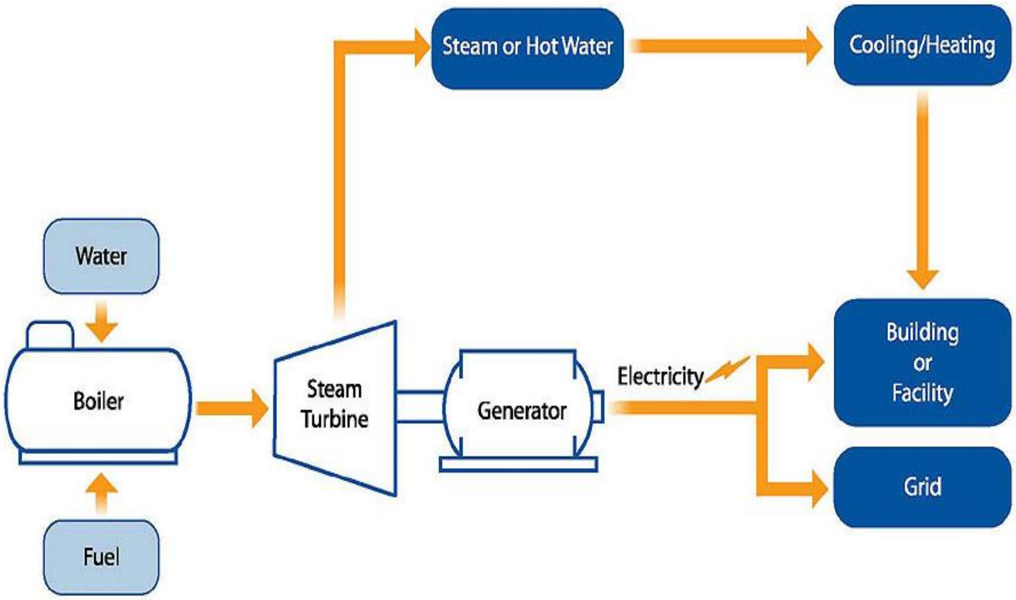


Figure 4 CHP system: steam boiler with a steam turbine [4]

There are many challenges for the CHP systems in lower power generation plants. As the lower power generated, the more increase in the production cost of electricity per kW. Moreover, the high cost of CHP system components is a challenge for implementing it in small scale cogeneration plants [4].

1.1.3 Combined Gas Turbine Systems

Conventional gas turbine cycles are very efficient and compact for power generation, yet they have low thermal efficiency. Additionally, there are many heat losses through gas turbine exhaust. Therefore, a combined gas and steam cycle concept has been introduced to recuperate these losses to generate more energy and increase the efficiency of the power system [5]. The air compression ratio is significantly affecting the efficiency of the gas turbine. As the increase in the compression ratio increases the efficiency gas turbine cycle, which escalates the power production of the whole combined cycle compared to the traditional Brayton cycle. Although the combined cycle has higher efficiency and power output, it does not have a free power turbine to handle the load fluctuations. Moreover, there is a limitation in primarily controlling the gas turbines in the conventional combined cycle power plants due to the passive operation of the steam cycle [6].

The layouts of the two primary combined cycles are presented in Figure 5. The left cycle (a) is a multi-shaft combined cycle, and the right cycle (b) is a single shaft combined cycle. They mostly have the same components such as Compressor (C), Power Turbine (T), steam turbine (ST), steam generator, condenser, combustion chamber, water feed pumps, and generators (G). The increase in the efficiency of either the Rankine cycle or the gas turbine directly elevates the overall efficiency of the combined cycle [5]. In order to increase the efficiency of the gas turbine cycle, the pressure and turbine inlet temperature should be raised. Another option to increase the efficiency of the steam cycle is by raising the pressure ratio over the steam turbine. This results in a higher pressure from steam generator along with lower condenser pressure, however, this action is mainly restricted by the available medium temperature for cooling the condenser such as normal water or ambient air [6].

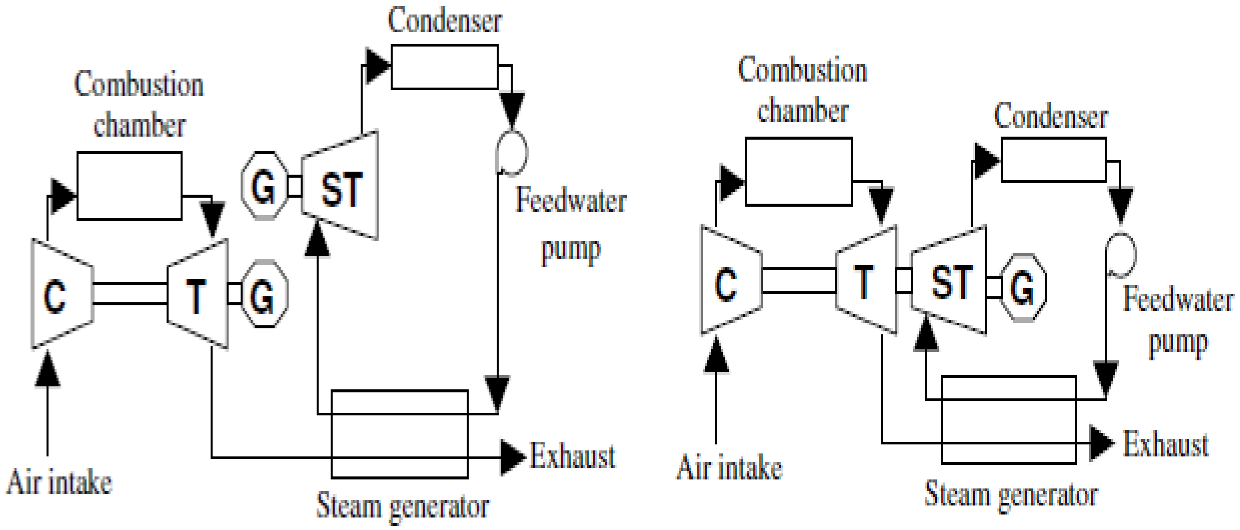


Figure 5 The multi-shaft combined cycle (a) and the single-shaft combined cycle (b) [7]

Usually, combined cycles take a long time for a start-up operation, which reaches up to several hours. This is restricted because of the steam generator, heat recovery steam generator and the plant design. Therefore, this procedure limits their ability to operate at flexible loads. That is why conventional combined cycles are only be employed for applications where a load of power generation from shaft power is 1000 MW [6].

The main difference between both of them is that the gas turbine and steam turbine in the multi-shaft combined cycle are connected to a separate generator on the contrary to the single-shaft combined cycle where both turbines are shaft connected to a single generator. The design of the single shaft results in a less initial capital cost and better efficiency than the multi-shaft combined cycle. On the other hand, the multi-shaft combined cycle can be advantageous and more economical than a number of single shaft units where phased construction or flexible layout are essential. Eventually, the choice of either configuration of the two cycles depends mainly on the load requirements and the value over life in different cases [6].

Finally, it is noted that the main drawback of the Rankine cycle is the long start-up operation time. In addition, the conventional combined cycle lacks the ability to handle power fluctuations. Thus, lacking this ability makes it difficult to operate these cycles at flexible loads, especially for electrical peak-shaving fluctuations.

That is what exactly created an industrial gap for introducing a combined cycle which has a free shaft power turbine capable of power fluctuations in rapid time response. This novel cycle is called Rankine Compression Gas Turbine (RCG), and it is introduced in the following section.

1.2 Thesis outline

Heat Power BV has been doing research and development of the RCG system for years. Different business models have been studied to find the most suitable way of entering the market. As it was shown before that many students have been doing their thesis work within the company to suggest more options and analyze the whole operation of the system with different components. So that the company has an overview of all the possible scenarios. Finally, the company decided to proceed with offering the RCG as an add-on feature as this has an impact on reducing the capital cost for the targeted customers, and it can be more feasible. That is why the company started developing a prototype at the Eindhoven University of Technology in order to be able to experimentally validate the concept of RCG add-on. A 5kWe RCG add-on prototype has been developed for that purpose, and it was successful. Later, the company wanted to implement the add-on in a real industrial context to attract more investors and clients. Fortunately, the company found a wood processing factory in the Netherlands which agreed to install the system in its facility. This is a massive milestone for the company to fully validate all the advantages of the RCG technology for tackling peak-shaving in a rapid response. This helps in commercially entering the market and starting the sales phase.

In this thesis, the implementation and installation of the RCG add-on at the HIS factory in the Netherlands are explained. This is the first real-scale pilot test for the RCG add-on in an industrial context. The design criteria for the chosen components and the operation process are be explained in detail. Moreover, some experiments have taken place later in order to;

1- Confirm the principle of the RCG add-on in an industrial environment.
2- Validate the rapid time response of the RCG add-on for flexible power outputs.
3- Demonstrate the capability of the RCG add-on for power fluctuations.
4- Obtain real data of the system's operation for future up-scaling of the RCG add-on.
5- Analyze a feasibility study for the RCG add-on system.

The methodology of the following sections is divided into sections. First, the design and technical considerations of the system is illustrated in addition to the criteria for choosing the setup components. Second, the installation at the HIS factory is explained, and the steps of designing the 5 kWe prototype are illustrated. Third, the discussion of the experimental results that took place after completing the installation is shown. Finally, the feasibility study of the commercial RCG add-on is studied along with several economic parameters.

2 The Rankine Compression Gas Turbine Technology (RCG)

This section illustrates the innovative concept of RCG. In addition, previous research has been done before for developing the concept. Additionally, the proposed system model for an industrial application is presented.

2.1 Technology explanation

The development of the Rankine Compression Gas Turbine (RCG) technology started as an alternative to conventional gas turbine systems. As mentioned before, there is an existing gap in the current energy production systems that they are economically feasible to implement and have high efficiencies only in large power production. For the case of a power range more than 1000 MW, a conventional combined cycle of Rankine cycle and gas turbine would be suitable. As combined cycles take a long time for a start-up operation, which reaches up to several hours. That is why there is a need to create a technology that is efficient and feasible in small scale power systems in a range of 1 to 10 MW [7].

In addition, it is challenging to operate conventional combined cycles at rapidly alternating speeds which limit their flexibility for electricity production fluctuations. The new installation of the RCG tackles this as it involves a novel combined cycle installation which returns all shaft power in the system to a one free power turbine. Thus, it sustains electrical peak shaving loads and performs with a rapid response [8]. Another essential feature of RCG, it acts as an add-on to existing installations such as furnace or boiler systems. In that case, the RCG add-on installation operates without affecting the steam characteristics in the system. With these features, it can be feasible to install the RCG for the various applications which could not be employed with the conventional combined cycles.

2.1.1 The novel principle of the RCG

The innovative principle of the RCG with comparison to other combined cycles is the distinct layout which results in a free power turbine. As seen in Figure 6, the RCG system is comprised of two primary cycles which are the gas cycle (Brayton cycle) and the steam cycle (Rankine cycle). Both cycles have the regular components of a steam boiler, a steam turbine, a compressor, a combustion chamber and a gas turbine connected to a generator. For the steam turbine cycle, an auxiliary burner (A) is connected to the steam generator in order to initially operate the cycle. The steam generator is making use of the exhaust gases to fasten the production of steam.

The gas turbine cycle includes an air compressor (C) which is shaft driven by the steam turbine (ST) of the Rankine cycle. This creates a free acting power turbine (T) and that is the reason for describing the cycle as the Rankine Compression Gas turbine (RCG) cycle. The Power turbine (T) produces the demanded loads (L) for the facility. In addition, the power turbine is not only driving the electrical generator but also other mechanical drives such as a compressor (C) or a pump. Correspondingly, this offers load flexibility in a very rapid time response within seconds while maintaining the steam conditions at the facility. Moreover, it can be a solution for electrical peak-shaving demand. This is a unique feature for a combined cycle.

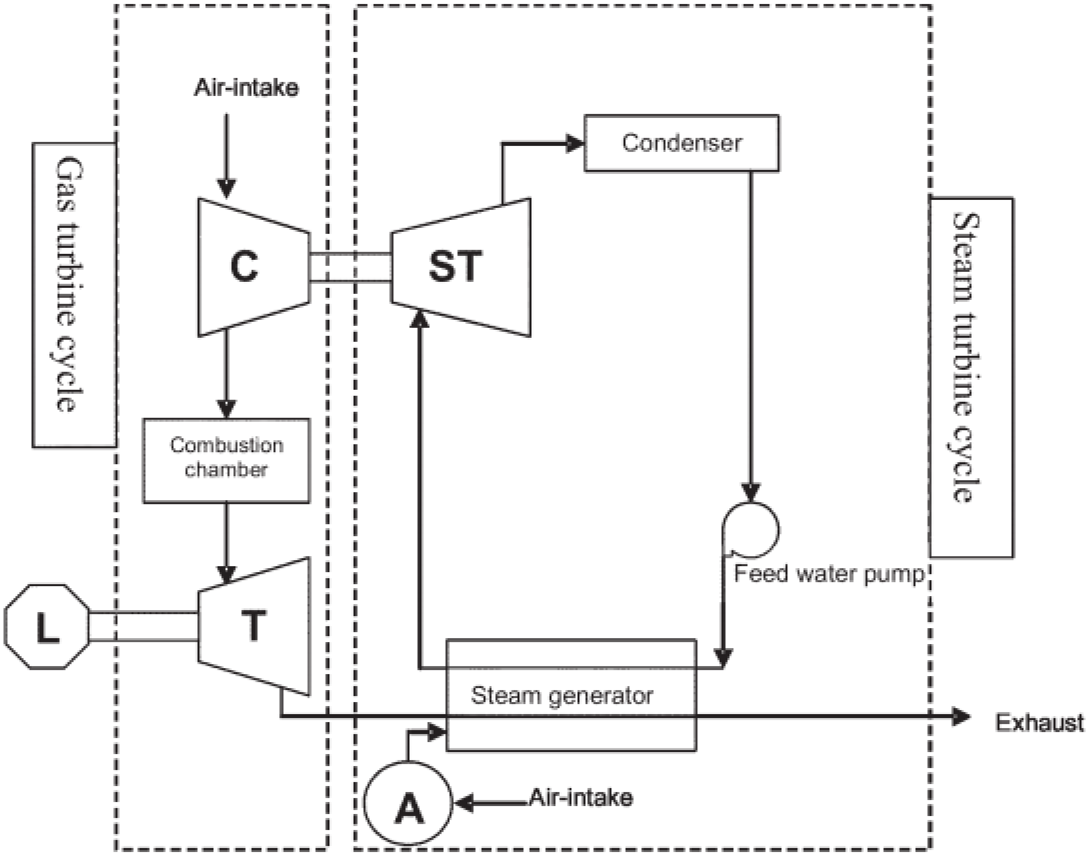


Figure 6 Principle of the Rankine Compression Gas Turbine cycle [7].

Little power is needed while starting the RCG cycle. As the power turbine (T) is in the standby mode until it receives sufficient hot gasses resulted from combustion in order to start generating the loads (L). The only consumed power while running the RCG is used for the burner. As a result, RCG can be implemented for many decentralized CHP applications in addition to the mechanical drive applications.

There is previous research that has been done for developing the RCG, and they are illustrated in the following subsection.

2.2 Previous research

In 2006, Ouwerkerk modeled [7] the RCG proof of principle using MATLAB. The basic choice of the RCG system components has been discussed to have an overall idea of the required equipment. Also, it has been concluded that most the components can be found in the market which confirmed the technological feasibility and robustness of the RCG. Moreover, a comparison among the RCG system, recuperative cycle and simple cycle was made using a computer model. A set of properties was assumed for different cycle like the efficiency of the used components, steam pressure and temperature and ambient temperature. Later, thermal analysis was done to measure the efficiency of the three cycles. The RCG system and the recuperative cycle has a thermal efficiency of 40 % at maximum turbine entry temperature. Also, the required pressure ratios for the RCG and recuperative cycle are much lower than the simple cycle at different turbine inlet temperature. In terms of Power rate, the RCG can generate up to twice the generator power of the simple or recuperative cycle. Further work was done regarding the techno-economic feasibility of the RCG system for the 2.5 MW and 10 MW systems with a final investment cost of 1,800,000 euros and 4,500,000 euros respectively. After that, there were many experimental investigations of the system to be further studied. It showed that the RCG can suitable for various mechanical drives applications. Later, a prototype was developed at The Thermo Fluid Mechanical Engineering Lab (TFE) of Eindhoven University of Technology to realize the technological feasibility of the RCG. The outcomes of this work has been formulated in a paper and it was published in the Applied Thermal Engineering Journal

In 2009, Ouwerkerk developed [8] and simulated a 1 MWe RCG system from commercial components as a part of his Ph.D. thesis. It was intended to use the system for CHP applications using natural gas or glycerol as fuel. The testing set-up was installed to verify the proof of concept of the RCG system as stand-alone system for large scale power outputs. A once-through boiler was used for steam generation due to its compactness and short start-up time of around 10 minutes. In addition, it was used to test the stability and durability of the whole system. It was concluded that thermodynamical equilibrium can be reached with pressure ratios of 3 to 4 which is suitable for conventional turbo machinery components. A restriction valve was used instead of the power turbine in order to understand the controlling strategy of the steam turbine. Moreover, the transient behavior of the system was observed, and a model was created. The results showed that the steam turbine operation was responsible for the transient behavior of the RCG. There was a need to measure the response time of the RCG while fluctuating the loads that is why a PID controller was used. Also, an auxiliary burner was installed in order to measure the cold starting time of the set-up. It was concluded that the RCG system could be well-regulated and controlled if there are certain control strategies for starting the steam cycle and driving the compressor. Later, the experimental results of the set-up were compared to the simulated results and they matched to high extent. Overall, this experiment validated the principle and the performance of RCG on a lab scale and it was proved that the RCG can obtain thermal efficiencies of 30 to 45 %. The response time of the RCG system from part load to full load was measured to be 450 seconds. Moreover, there were some financial calculations to give an overview of the cost planning for the RCG system for large scales of 1 to 10 MW. Finally, there were some recommendations and suggestions to be considered for scaling up the testing set-up in the future to validate it under same boundaries of a real scale installation. Also, the transient behavior of the whole system should be further optimized according to the obtained results from this experiment.

In 2014, Solorzan Master’s further investigated [9] the response time of the RCG. The same setup was used from Ouwerkerk's previous work. There was still an auxiliary burner for starting the set-up along with the use of a restriction valve instead of a power turbine. However, there is a new installment which was a hybrid electric overdrive in order to run the compressor. Based on the previous suggestion, three controlling strategies were taken into consideration. For the operation of load fluctuations, a transient model was established. The response time was measured while shifting from partial to full load. The measurements showed that this operation happens within seconds and it was even lower in time than the initial setup that was done before by Ouwerkerk.

In 2015, Mortel introduced [10] the power turbine along with the electric generator to the RCG set-up instead of the restriction valve. In addition, a steam separator was installed to get rid of the drained water. The objective of this thesis is to produce real power while operating the RCG system. That is why the whole set-up was upgraded with the proper installation of piping, sensors for measurements. A numerical simulation was developed to calculate the response time of the RCG system. In addition, there was further development in the controlling and operating strategies of the system. The experimental operation of the set-up started for the warming-up experiment from cold then later with the full load operation. Some technical problems were tackled during the experiments such as, leakage from the water pump and some electrical connections of the measuring sensors needed to be changed.

In 2016, Emonts examined [11] the production of electricity from the RCG system of the former cases. A new installation of a lubrication system for the RCG set-up with the addition of oil cooler. A mixer was added which combined the auxiliary burner products with the exhaust gas from the power turbine. The previous control strategies were used with some developments for the starting procedures of auxiliary systems and safe operating conditions. Emonts estimated the time for both scenarios either with the hybrid electric drive or the auxiliary burner to be 50 seconds and 200 seconds, respectively.

In 2017, Jungman focused his work on obtaining a steady production of electricity while stabilizing the RCG system set-up [12]. Jungman continued to work on the RCG lab prototype that was already developed and improved by the previous master students. The prototype had some issues with instability and some components failures. Jungman worked closely on improving the performance of the setup and the overall control of the system to regain its stability to achieve stable generation of electricity. There was a process of replacing some of the designed or failed components. Also, there was an addition of implementing the indirect heating principle. This was done by installing a heat exchanger to transfer the heat to the working fluid instead of the direct method of combusting the injected fuel. The heat exchanger was designed to have a heating capacity of 1.5 kW for indirect heating. A realistic mathematical model was developed, including the flow losses of the system. Moreover, a new operational strategy was created using a mathematical model. The model was validated by doing experimental work. It showed that the operation of the steam generator was steady. As the main focus of Jungman was to generate electricity from the system, the set-up was fully modified for that purpose, and the final electricity production of the set-up was 100 W for 30 minutes duration. The generated power was very low due the limitation of the auxiliary burner for running the lab prototype. This limits the steam boiler because of the limited power of the auxiliary burner. The maximum thermal power that could be achieved was 300 kW. Also, there are other limitations like the burner temperature and the parasitic losses which consumed around 50 kW of the total thermal power. Some recommendations were set at the end of the work regarding the development of new control system and the enhancement of the safety features of the system. Moreover, the gas cycle should be further assessed with the focus on the pressure ratio, air flow, power generation and the speed of the turbine.

Finally in 2018, Carrion developed [13] a time-based model that represents the dynamic behavior of the RCG system components was done through the MATLAB-Simulink interactively and efficiently so that the various input parameters from industrial organizations can be assessed. This resulted in a robust model to study different systems in which RCG can be implemented. This model was intended to be used for two main requirements: the evaluation of the transient behavior of the RCG and the estimation of the system's performance for different parameters. Also, a thermodynamic analysis review was done to fully understand the system along with the advantages and disadvantages, Additionally, Carrion modeled a 40 kWe pilot RCG to investigate the system further and assess its components by modifying the model. Later on, he upgraded the model to 100 kWe RCG system while trying to adapt many scenarios of the installation of the compressors and turbines either in parallel or in series.

2.3 Proposed system

Heat Power BV, which is the name of the company that developed the RCG technology and holds the RCG's patent, has been analyzing several business scenarios intending to enter the market. It has been decided that the company focuses on a particular application and do a pilot test to experimentally validate the RCG principle in an industrial context. Thus, the concept of RCG as an add-on has been developed.

As shown in Figure 7, the proposed process scheme of the RCG add-on is presented for an existing industrial steam system. Usually, it is required to regulate the pressure of the steam for different processes which is commonly done through the installation of an expansion valve. 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.

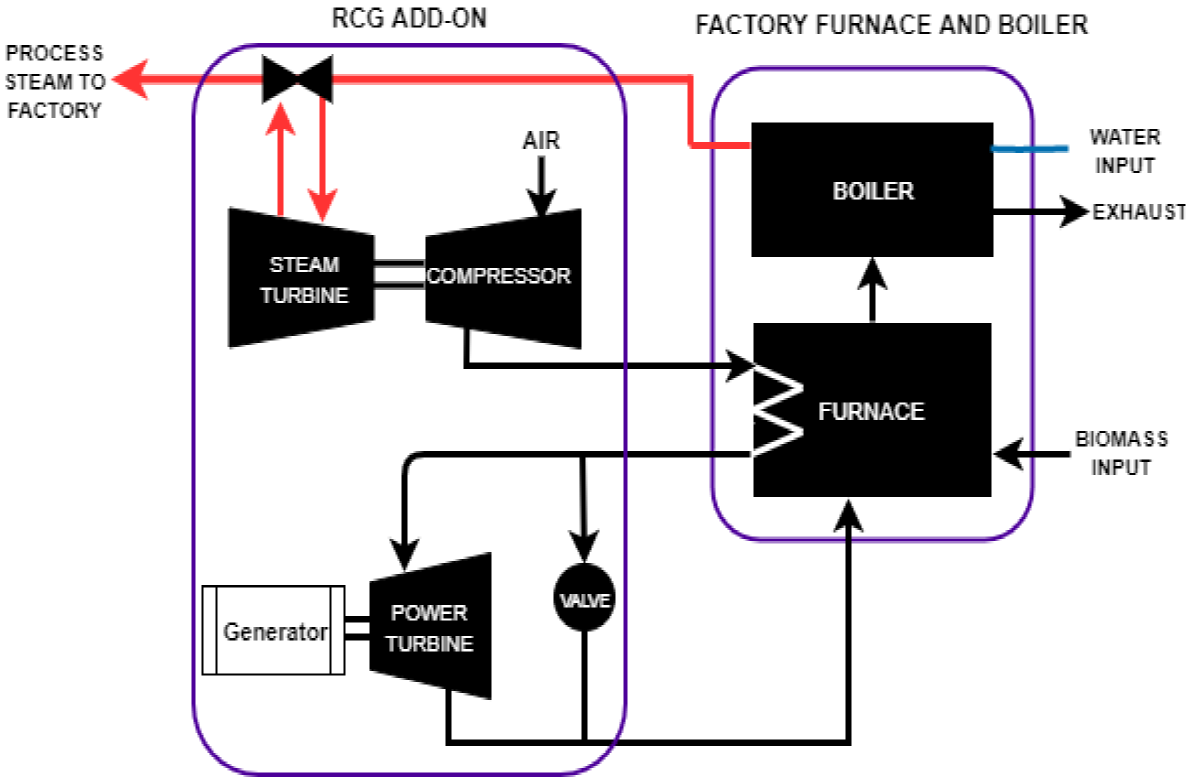


Figure 7 Process diagram of RCG add-on (patent EP1492941 and PCT/NL2017/050505) [14]

3 Technical assessment

In this section, the design components of the RCG add-on is illustrated. The main aim is to design the prototype of a system which is used in the first industrial case for the RCG add-on. This acts as a proof of principle for the RCG cycle in an industrial context and will be the base for upgrading the system to a commercial scale. The choice and arrangement of the main components of the system are discussed.

3.1 System components considerations

There are some design considerations that should be assessed for the RCG add-on system. First, the feasibility of the system components is analyzed. The planned RCG add-on is on a small scale power generation system, and it takes some time and effort to find the most suitable and commercial equipment. Usually, the equipment with high technology is suitable and efficient for large scale power plants but not for small scale. For example, the implementation of an efficient steam turbine in a large biomass plant in order to generate electricity.

The available products in the market have been checked because they are cheap, and they do not need any engineering customization to be implemented for the RCG add-on. Although customized products for the RCG add-on can be a better choice in terms of performance and efficiency, however, they are up to 30 % more expensive than the off-the-shelf products.

An evaluation has been made for the main required components of the system to check the availability, technology, and cost in order to narrow down the options. So, each component was analyzed separately in the subsequent subsections.

3.1.1 Steam turbine

While choosing a suitable steam turbine, the technical and economic aspects should be considered. For the technical part, two main types of turbines are evaluated for the selection: the reaction and impulse turbines.

There are some differences between the reaction and impulse turbine that determine which one is suitable for the RCG. As seen in Figure 8, the expansion in the reaction turbine is partially done in the inlet stator, and the rest is done in the running blades. The steam pressure falls gradually while passing through the blades. Also, the velocity of the steam decreasing while running the moving blades. For the impulse turbine, there is a nozzle which is responsible for the whole expansion process. It assists in generating high pressurized steam with a high velocity that is transformed into mechanical energy while running the blades of the turbine. The blades have a bucket form. The steam pressure remains constant while running the moving buckets but the velocity decreases [18].

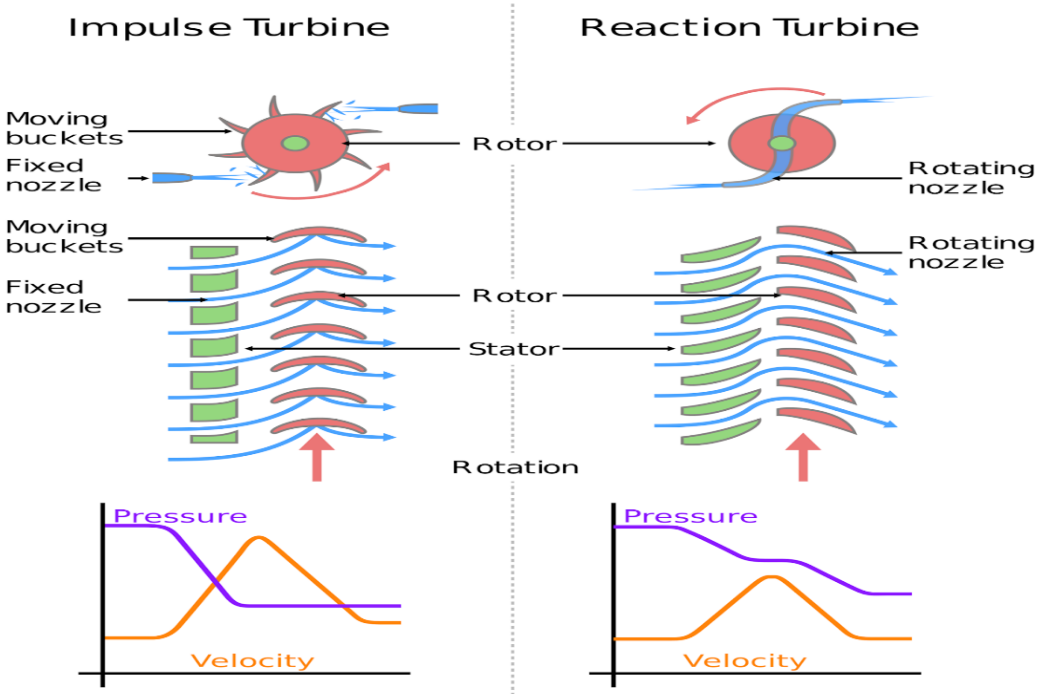


Figure 8 The difference between impulse and reaction turbines [17]

There are also some characteristics of both turbines which affect the selection criteria. Mostly, it is in favor of the impulse turbine for the RCG add-on case. For small steam volumes, the impulse turbine has a better efficiency even while having higher pressure ratios. Moreover, it has relatively less number of stages compared to the reaction turbine. Also, it has more extended maintenance periods and better lifetime reliability [19]. Overall, the impulse turbine is favorable for implementation due to its lower costs and applicability for lower steam flows and high-pressure ratios.

From a commercial and efficiency perspective, a small scale turbine can be found in the market, either a multi-stage or single-stage one. However, the required efficiency plays a role in the choice with a range of 40 % for the single-stage and up to 65 % for the multistage. These efficiencies are also a challenge for the small scale cogeneration power plants as it can reach up to 90 % for large scale power plants [4].

3.1.2 Compressor

There are different categories of compressors, and each has its advantages and drawbacks. As shown in Figure 9, the applicability for each type of compressor is affected by the mass flow and pressure ratio. Based on the working requirements, the centrifugal and axial compressors are considered to be the most suitable for the RCG add-on cycle. The air flows perpendicular to the rotation of the axis in the centrifugal compressor and leaves in a radial direction while it flows in a parallel direction for the axial compressor. It is seen that the centrifugal compressor is applicable for lower mass flow rates, and they can operate for higher pressure ratios compared to the axial compressor [20]. However, the axial compressor can result in higher peak-efficiency, but it is lower in the off-design, which makes it less robust [21].

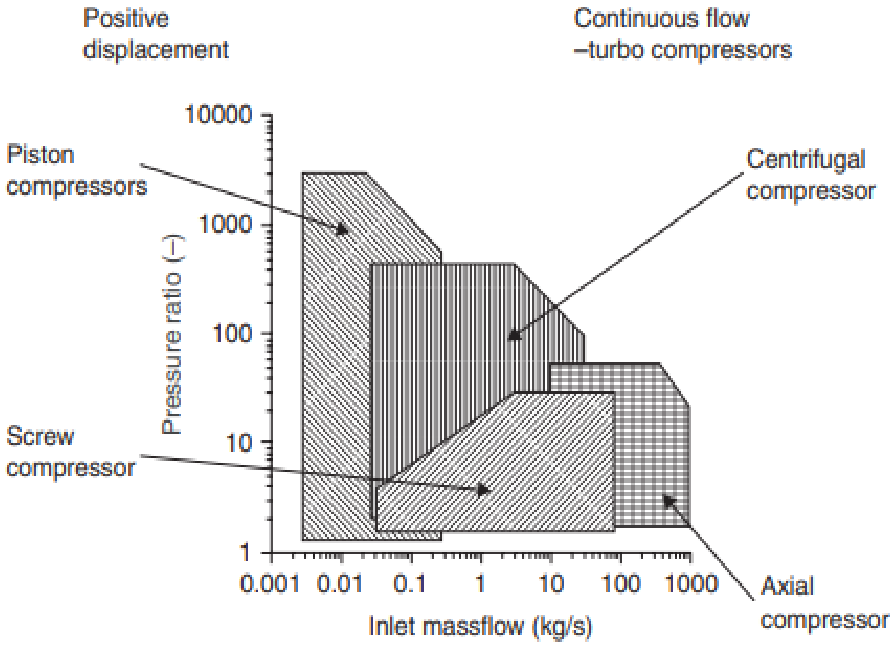


Figure 9 Different types of compressors and the required pressure ratio and mass flow [20]

According to this analysis, the centrifugal compressor seems to be a good fit for the RCG add-on cycle. As it can operate with a low airflow rate at multiple points. There are two types of centrifugal compressors that are single-stage or multi-stage. The multistage compressor is applicable for a relatively more extensive range of operating points and it is more expensive than a single stage. However, the single-stage compressor is more efficient with a range of up to 80 % compared to the multistage compressor, which has 60%-72% efficiency [21]. Thus, the single-stage is more preferred for the RCG add-on application due to lower cost and there is no significant difference for the range of operating points [21].

3.1.3 Heat exchanger

Many parameters affect the choice of the design of the heat exchanger. First, there are many designs of the heat exchangers, as seen in Figure 10. Thus, the choice is different from one project to another as the properties of the hot flue gasses and the compressed air are different in every project. This also affects the type and cost of the insulation material of the heat exchanger. Second, the installment of the heat exchanger into the furnace may require a customized one for each furnace. These parameters make it difficult to find a commercially produced heat exchanger in the market without any customization. Thus, it is costly to have customized exchanger. However, the aim is to find a compact and efficient heat exchanger for the RCG add-on application [22].

Usually, the counter-flow heat exchanger is the most effective configuration. However, the cross-flow heat exchanger is preferred in this case due to the limited installment space in the boiler/furnace. So, the bundle tubes design is used for the heat exchanger as it is more flexible and compact for the RCG add-on system. Also, it can be a reason for having a lower cost heat exchanger for the RCG add-on.

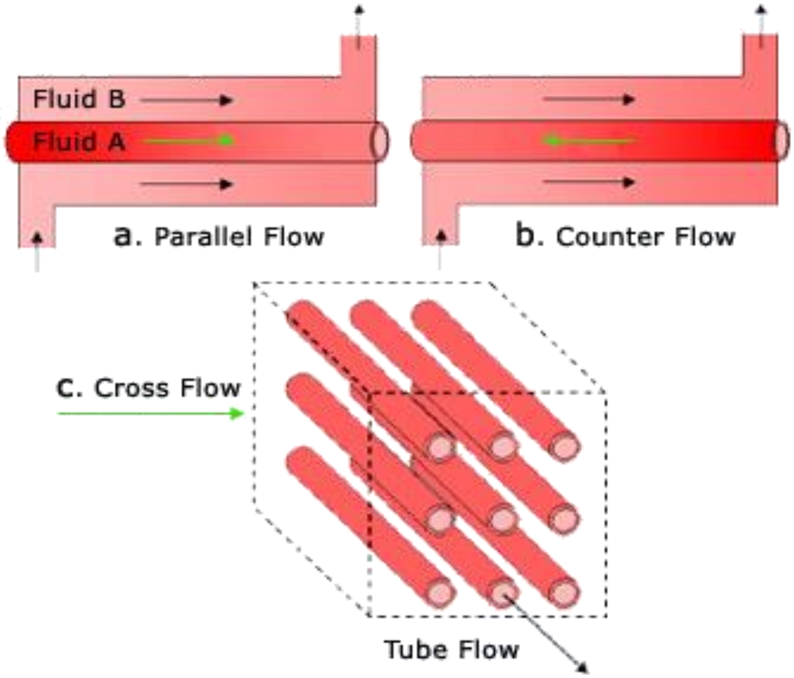


Figure 10 Different types of fluid flowing for the heat exchangers [22]

The performance of the RCG add-on heat exchanger is mainly affected by two parameters: the pressure drop and the outlet temperature of the compressed air. Each parameter affects the power output of the gas turbine differently. The power output is directly proportional to the compressed air temperature and inversely proportional to the pressure drop. As the compressed air temperature affects the power output of the RCG add-on cycle. The higher the temperature of the air can reach, the more power output is generated. For the pressure drop, it results from the flowing of air from the pipe into smaller tubes then it returns back to the pipe again. The pressure drop reduces the power output of the power turbine. The pressure drop can be tackled by having a low flow speed as it is directly proportional to the square root of the speed of the flow. However, the convection coefficient can be reduced due to the low flow speed. Thus, some trade-offs should always be evaluated while designing the heat exchanger [22].

3.1.4 Gas turbine

The gas turbine has the same types as the compressor, which is centrifugal or axial. They also have the same differences, as explained in the compressor section. The centrifugal turbine needs fewer stages for the expansion process, which makes it a cheaper option. Also, it is applicable to lower power outputs. Although the axial turbine has a better peak efficiency, the centrifugal turbine is more robust [21]. Thus, it is preferable to use a centrifugal turbine for the RCG add-on.

For the market search, not many turbines are available as an existing off the shelf stock. Thus, another option is to consider the turbocharger turbines due to its availability. It consists of a turbine housing and a turbine wheel and it converts the combustion exhaust gases to mechanical energy to run an attached compressor. This compressor feeds the air to the power engineer and thus the efficiency is increased.

Turbocharger turbines have an isentropic efficiency in a range of 65% to 80% and they are considered as a feasible solution for the RCG system [21].

4 RCG add-on setup in industry

The RCG add-on setup design has been realized for installing it at Houtindustrie Schijndel factory (HIS) in Eindhoven, the Netherlands. HIS is a wood processing factory that has already an existing steam generation system and biomass furnace. Heat Power BV signed an agreement with HIS factory to install the 5 kWe RCG add-on in their facility in order to demonstrate the principle of the system [15]. There were already many components that were used for previous RCG setups which can be part of the add-on system. Now, it is even easier to construct the add-on as the steam generation components are excluded because there is already an existing system at HIS. Only a steam turbine is needed to run the air compressor.

Several considerations are taken during the installation of the RCG add-on at HIS. First, the steam conditions of the factory should not be disturbed while running the RCG add-on. A new platform has been built at HIS factory so that the RCG add-on setup can be built on it. The steam tube connection for the steam turbine is installed on the tube which connects the expansion valve with the factory’s main streamline. Moreover, the expanded steam is injected back to the mainline of the factory without affecting the steam conditions.

The RCG technology can be evaluated according to the Technology Readiness Levels (TRL) which examines the maturity level of a given technology with respect to given requirements, concepts and demonstrates capabilities [16]. As the RCG add-on has been already experimentally tested and validated in a laboratory context at the Eindhoven University of Technology, it can be reflected as a TRL4. Thus, the implementation of the RCG add-on in an industrial environment which is HIS factory, in this case, upgrades its readiness level to TRL5 [16].

4.1 Preliminary 3D design

A suitable location was found at the HIS factory to build the RCG add-on platform. Fortunately, it was near the steam expansion valve and the main water tank of the factory, as shown in Figure 11. The dimensions of the platform were measured and it is a 2 m width, and it should be 5 m above the ground level. Two I 400 sized profiles was already built to handle the platform and they have a space distance of 4.03 m between each other. A walking path was already taken into consideration to access the setup. Then, a crane was used to lift all the components up to the platform and connect them there.

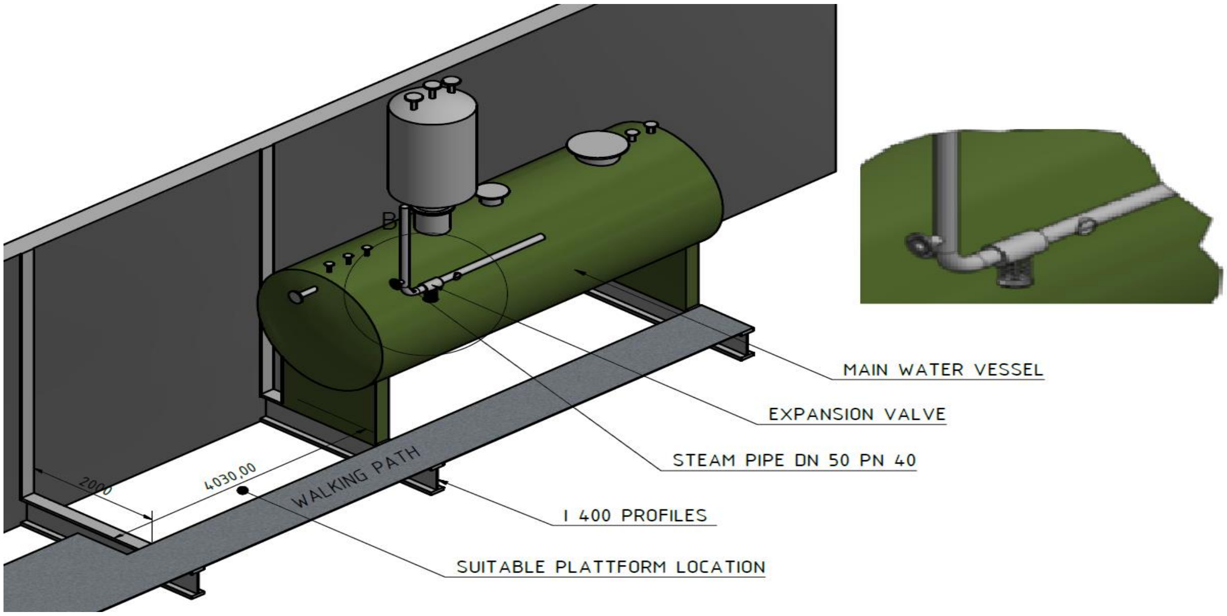


Figure 11 Suitable location for the RCG add-on prototype [13]

All of the main components of the RCG add-on model are shown in Figure 12. According to the installation structure at HIS, the input and output branches of the RCG porotype are connected to the steam stream pipe which connects the steam boiler and expansion valve. There is a connecting flange DN 50 welded in front of the expansion valve in addition to a manual steam valve installed on the flange. For the output branch, another steam flange with a size of DN 100 attached to a steam valve is installed behind the expansion valve. The primary role of the steam valves at the input and output of the RCG prototype is to provide proper safety isolation for the system if needed anytime.

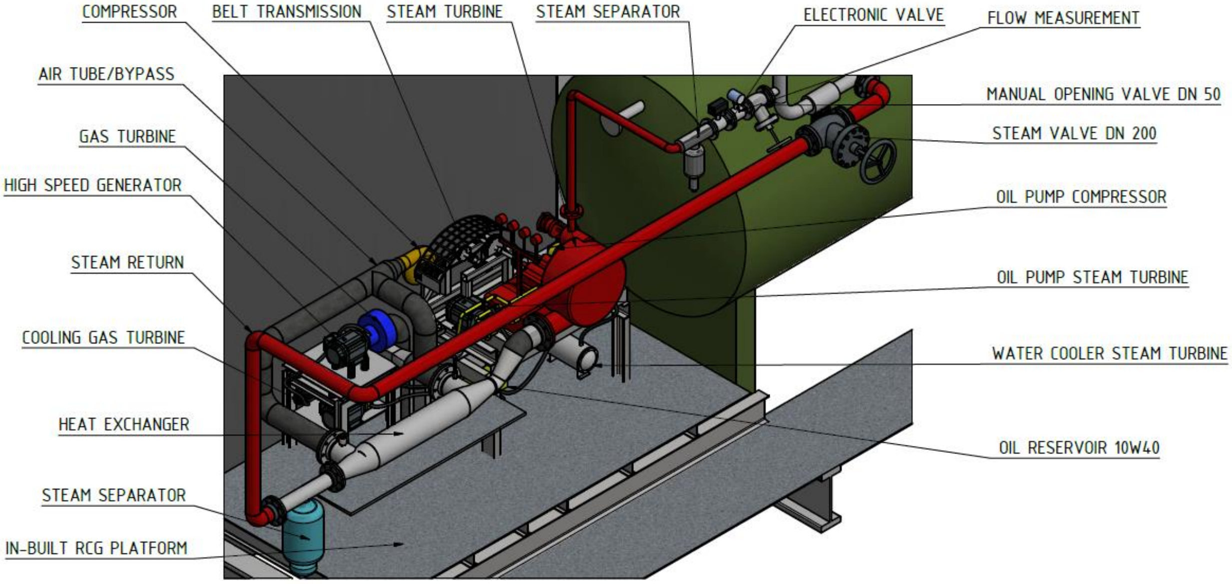


Figure 12 The basic RCG add-on composition [13]

For the installation at HIS factory, the RCG add-on prototype modeled to consist of three construction parts which are called KIT 1, KIT 2, and KIT 3 as shown in Figure 13.

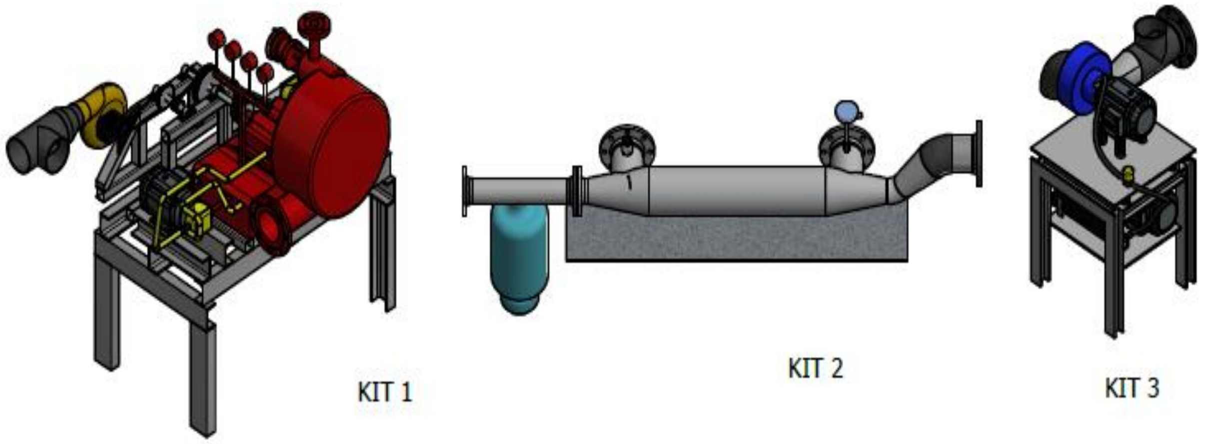


Figure 13 Construction under assemblies: KIT1, KIT2, and KIT3 [13]

Fist, KIT 1 includes the carrying frame of the system in addition to other components. The Steam turbine, which is red-colored in the figure is placed over the frame and it is connected to a lubricant oil pump. There is the air compressor which is also connected to an oil pump, and it is connected directly to the shaft of the steam turbine through a belt transmission.

Second, KIT 2 consists of the heat exchanger and the steam separator. Both of them are connected flanges with a size of DN 150. The heat exchanger is installed on its own designed frame and has a direct connection to the steam turbine. The separator is placed near the output of the heat exchanger.

Finally, KIT 3 consists of a frame that holds the power turbine and the generator. The power turbine is connected to the generator. Also, there is an oil pump connected to the turbine. The frame is comprised of four shock absorbers for absorbing the vibrations of the power turbine to make it more stable.

Overall, the KITs are entirely formulated to meet the installation requirements at HIS factory. The whole RCG add-on setup is constructed by connecting all the three KITs.

A 5 kWe small scale prototype has been designed and fabricated based on the technical assessment which was done before. The main components of the 5 kWe RCG add-on at HIS are shown in Figure 14. It is composed of a steam turbine (ST003), an air compressor (CP002), a heat exchanger (HE004), a power turbine (PT005) and an electrical generator (GE006) which is connected to the power turbine. The electrical generator system is robust and can perform at high angular velocities in order to match the power turbine high RPM. Thus, it is suitable for power fluctuations. Additionally, there are some control valves and measurement sensors that are linked to a control panel (CC012) in order to monitor the whole operation. Moreover, there is auxiliary equipment such as safety valves, connections, and auxiliary equipment.

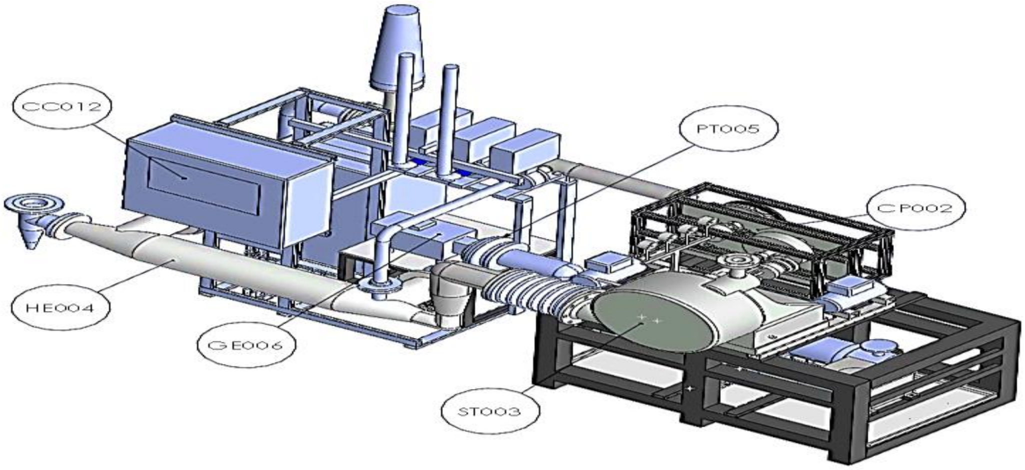


Figure 14 3D design of the 5kWe RCG add-on [13]

4.2 RCG add-on at HIS

The successful implementation of the RCG add-on at HIS validates the RCG novel concept as an add-on feature for industrial systems. The generated steam at HIS factory is produced by a biomass furnace that is connected to a steam boiler. The factory is producing high pressurized steam and there is an expansion valve to decrease that pressure from 29 bar to around 1.4 bar so that it can be used for wood processing. Although the RCG add-on is using part of this high pressurized steam for its operation, it is returned back to the mainstream of the factory with the same properties without affecting the steam conditions. The part of the steam that is used by the RCG add-on runs a steam turbine (ST003) which drives an air compressor (CP002). Then, the compressed air is preheated by going through a heat exchanger and injected into the power turbine cycle to have more efficiency. Thus, a free power turbine is available for power fluctuations and peak-shaving. The fabrication of the RCG add-on has been done at the Energy Technology lab at TU/e University as shown in Figure 15.

Figure 15 Fabrication of the RCG add-on at the lab

Figure 16 shows the transportation of the RCG add-on to HIS factory to be directly installed.

Figure 16 Transportation of the RCG add-on to HIS

The flow diagram of the RCG add-on is illustrated in Figure 17. There are three different flows which are represented by three different types of lines. First, the solid gray line shows the steam flow along the RCG cycle and then re-inject it back to the factory steam line. For the isolation of the RCG add-on cycle from the factory, there are two manual valves (HV007&HV010) installed at the inlet and outlet connections of the cycle to the mainline. Also, there is a butterfly valve (BV008) at the inlet of the RCG add-on cycle in order to control the flow pressure of the steam inside the cycle.

Second, the black dashed line shows the airflow through the compressor, heat exchanger and the power turbine. The power generation is affected by controlling the flow of compressed air. Thus, flow control valves (FH120A&B) are installed in order to regulate the airflow quantity to the power turbine. Also, there is a butterfly control valve (BV009) in order to bypass the air from the heat exchanger.

Finally, the solid black line represents the main steam stream of the HIS factory. There is an installed expansion valve in order to decrease the pressure of the main steam in order to use for the wood processing processes. There is a concern about avoiding the steam backflow whenever the steam line is over-pressurized while connecting the cycle stream with the main steam. Thus, a butterfly valve (HV011) is installed at the outlet line of the RCG add-on.

There are different types of sensors connected to the system, as shown in Figure 16 for measuring pressures, temperatures, current, and velocities. All the data signals can be shown in the control unit. The temperature sensors (TE211&TE213) are installed before and after the steam turbine, respectively. Pressure sensors (PT210&PT212) are installed in the same way as the temperature sensors. For measuring the angular velocities, speed sensors (ST105 & ST500 & ST501) were installed to measure the velocity of the connecting shaft of steam turbine and compressor, electrical generator and the connecting shaft between the power turbine and the generator. The current was measured with an attached sensor (ET502) to the generator.

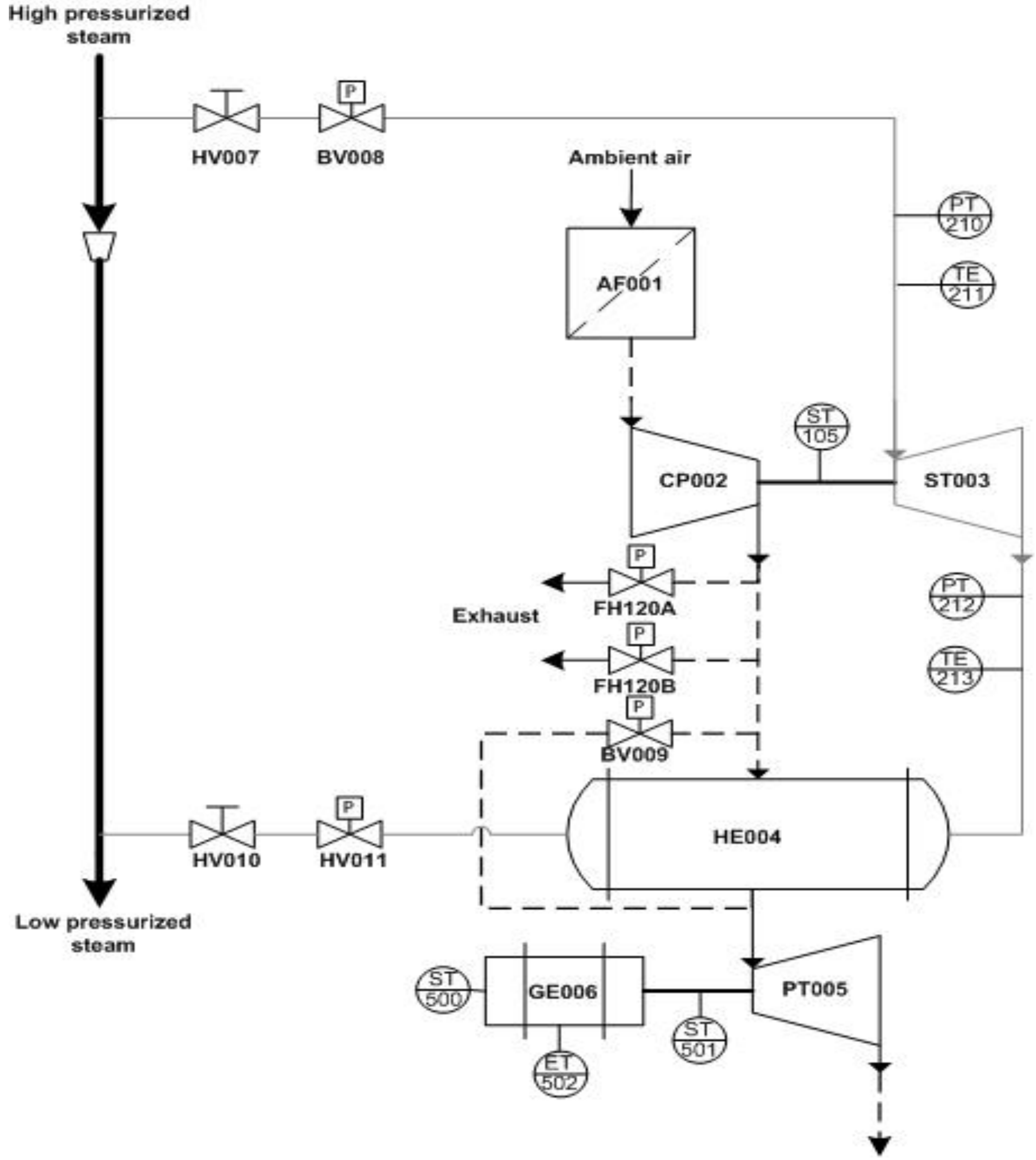


Figure 17 PFD of the RCG add-on cycle at HIS

In addition, there are be two water traps installed in the system. One is placed before the steam turbine in order to prohibit the water droplets in order to protect the steam turbine from damage. Another one is installed after the steam turbine to capture the water droplets which can be transported within the system. At the end of the process, the steam is reinjected again to the factory mainline for further using it in its processes.

Figure 18 shows the actual RCG add-on installation with its control panel that operates all the valves and data-acquisition.

Figure 18 The 5kWe RCG add-on at HIS

5 Experimental results and discussion

Experimental work for the 5 kWe RCG add-on has taken place and the results are discussed in this section. The main aim is to demonstrate the performance and working principle of the RCG add-on as a feature for an industrial system. The discussion of the results is focused on confirming the rapid response of the system within seconds for peak-shaving.

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. The accuracy of the temperature sensors are within (0.1+0.0017*absolute value of temperature in °C) and the pressure sensors error is less than 0.5 %.

This process shouldn’t affect the steam conditions of the factory by any mean. With these conclusions, the factory can decrease its dependency on the grid electricity and run the RCG add-on whenever there is a high electrical peak-shaving demand. This decreases the electricity bills for the factory as there will be no peaks in their energy consumption profile which causes higher electricity pricing. These results may be published later as a journal paper for The Applied Thermal Engineering.

5.1 Overall

After installing the RCG add-on at HIS**,** a day and time are decided to operate it for testing and do the needed experiments. The testing period took almost 90 mins. Several experiments have been done while operating the RCG add-on. At the start of the operation, a safety run test took place to ensure all the precautions before the actual experiment. 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 stated before, there is a control unit for the system which can be accessed for monitoring the results and varying the parameters. The focused parameters for the experiments are power output, steam pressure and temperature. As shown in Figure 19, the output power in Watts is presented throughout the whole period of the operation in seconds.

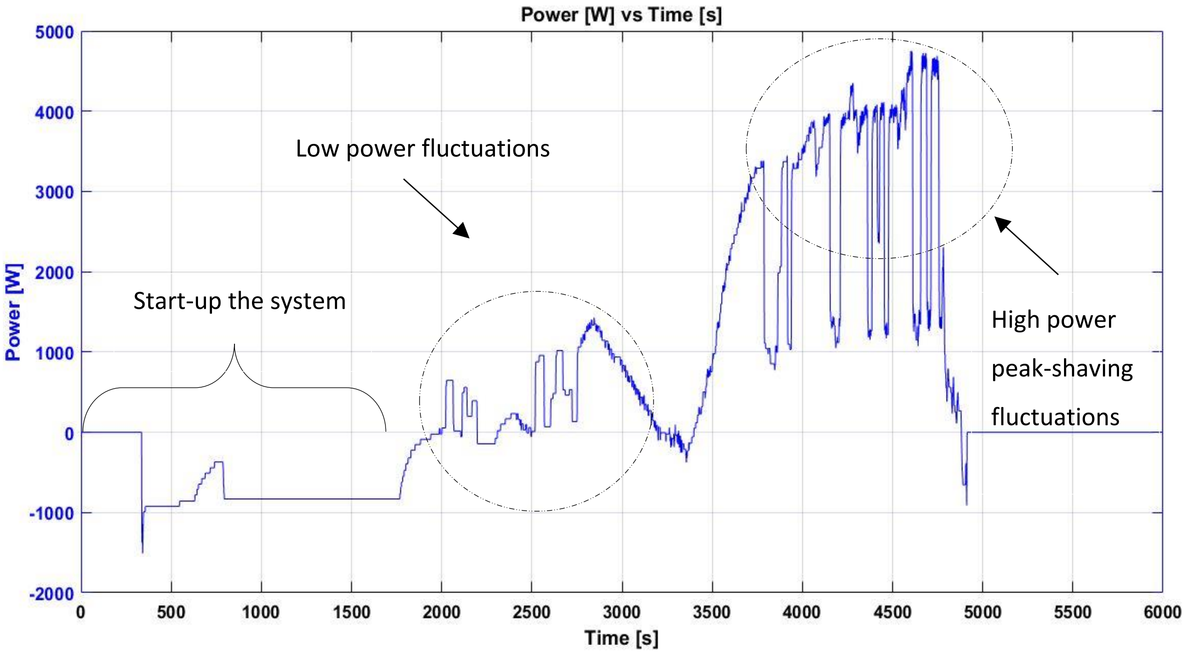


Figure 19 Overall power output of the RCG add-on cycle

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.

5.1.1 System start-up

First, the system needs to be started and warmed up to start the operation of the RCG add-on. Thus, the steam is injected into the cycle in order to run the steam turbine and such action happens by controlling the steam valves (HV007 & BV008) in order to vary the pressure of inlet steam. Some of the saturated steam energy is used to run the steam turbine (ST003) to power the whole cycle. The rest of the steam is fed through the cycle to heat up the pipelines and pass through the heat exchanger which is used to heat the compressed air. The residual steam is reinjected back to the main steam line of the factory while maintaining the required steam conditions of the factory.

The process of starting and warming up the steam cycle of the RCG add-on takes time as much as any other normal steam cycle. The timing for this stage is around 30 mins. The moment the steam cycle is already operational, the rest of the RCG add-on is on standby mode and can perform peak-shaving whenever needed. Therefore, it is important to heat up the components of the cycle by injecting various intervals of steam inside the cycle. There are water separators for removing the condensate. On the other hand, the power control valves (FH120A&B) are opened during this stage while closing the bypass valve (BV009).

There is some power consumption in this stage. This is due to the synchronization process between the generator and power turbine with the control of the frequency converter to overcome the friction and reach the zero power point before the beginning of the peak-shaving stages.

The final condition of this stage is to have the power turbine cycle in a standby mode while continuously running the steam cycle. This is a kind of preparation in order to achieve a rapid response to power fluctuations in the next two stages. The power output is positive in the next stages which shows the produced power output from the RCG add-on system to fulfill the required demand of the factory. The power fluctuates depending on the input parameters of the systems. This is demonstrated in detail for the upcoming peak-shaving stages.

5.1.2 Lower power peak-shaving

After warming up the RCG add-on system, a lower power fluctuations stage has started. For this stage, 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. The steam cycle is always operating and the steam is entering the cycle then reinjected back to HIS factory without affecting its condition. This is always the base case for the RCG add-on as the power system is decoupled from the steam system. Thus, if the steam cycle is always in the standby mode to run the power cycle, this enables a rapid response of the power cycle within seconds to fulfill the load flexibility demand. The control of power control valves (FH120A&B) either by closing both of them or only one contributes to the variation of the power output. This depends on the required power demand of the factory.

Figure 20 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. This process continued for the rest of the interval while changing the valves' settings. These experiments show that (within resolution accuracy) the power valves can be used as power switches at these settings between approximately 0, 450 and 1000W.

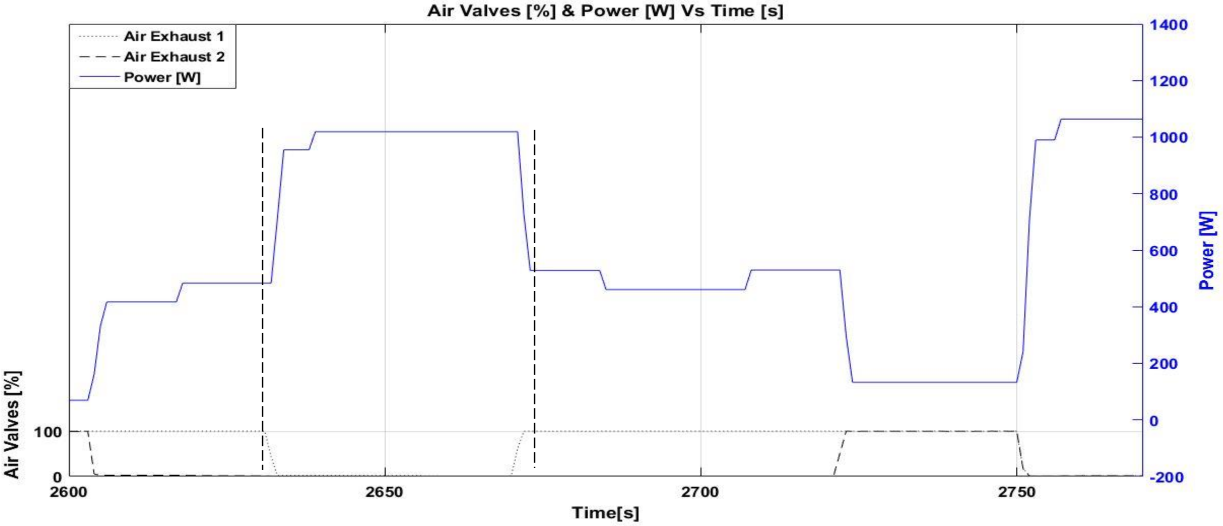


Figure 20 An interval of the lower power peak-shaving showing the relation between the power output and the change of power air valves' settings

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 21 during the same time interval as shown in Figure 20. 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.

These values are within the limits set already by the factory to not negatively affect the wood processing operation at the factory.

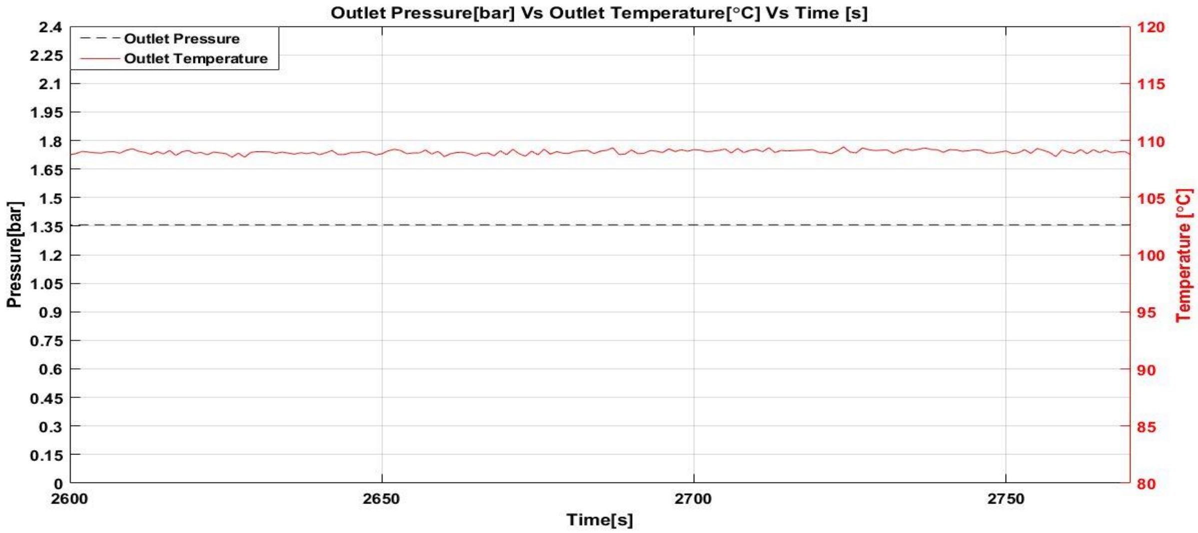


Figure 21 The outlet temperature and pressure of steam for the lower power peak-shaving interval

For a better illustration of the time response of the RCG add-on, a smaller time interval (2625s-2680s) is shown in Figures 22 and 23. Figure 22 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 around 1s.

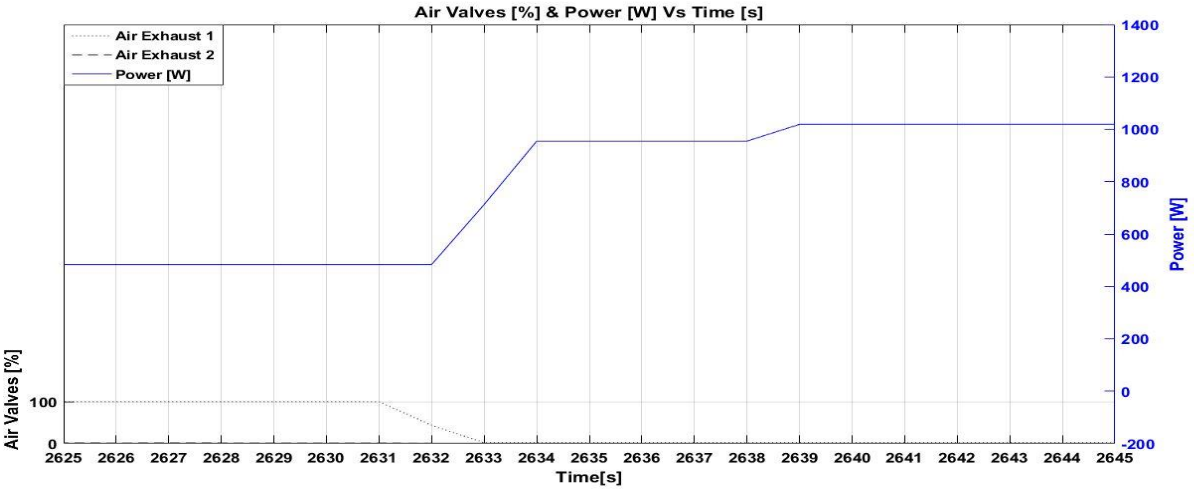


Figure 22 A chosen time interval (2625s-2645s) while closing both power air valves for lower power peak-shaving

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 23 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 21 and 22 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.

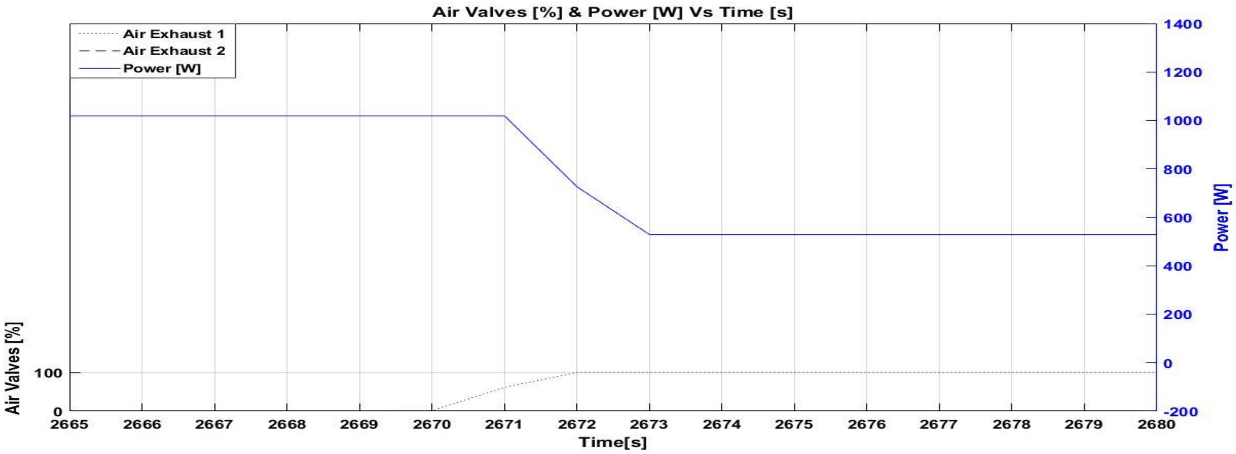


Figure 23 A chosen time interval (2665s-2680s) while opening one air valve for lower power peak-shaving

5.1.3 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 24, the power output fluctuates along with the time interval in seconds and this shows the impact of altering the settings of the power valves in order to achieve higher power outputs for peak-shaving. 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 25 shows the outlet steam pressure and temperature for this stage to check the steam conditions at the RCG add-on outlet. Both of them are almost constant during the whole duration and they satisfy the constant steam outlet pressure and temperature to the factory.

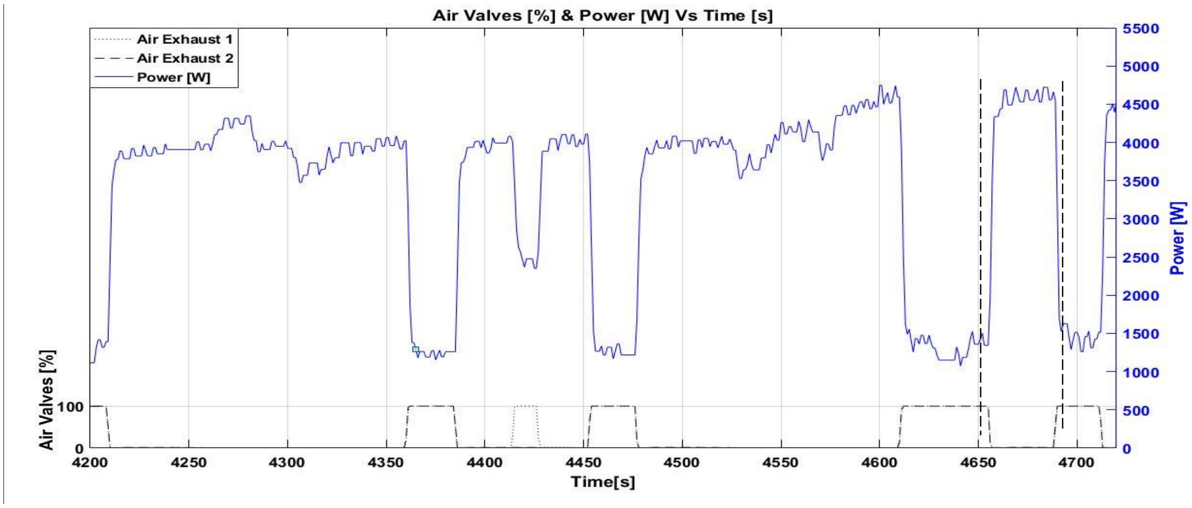


Figure 24 The relation between the power output and the change of power air valves' settings in terms of time response at the High peak-shaving stage.

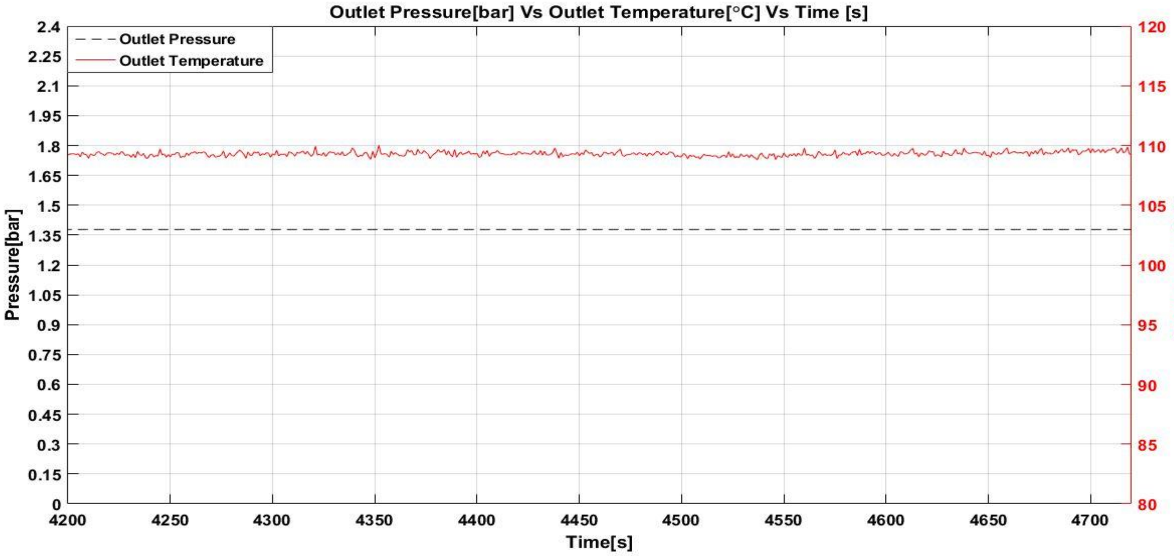


Figure 25 The outlet Steam pressure and temperature for the higher power peak-shaving stage

Figures 26 and 28 shows a close up of the power transients. As shown in Figure 26, 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. Figure 27 shows the pressure and temperature of the outlet steam at the given interval are still constant as previous.

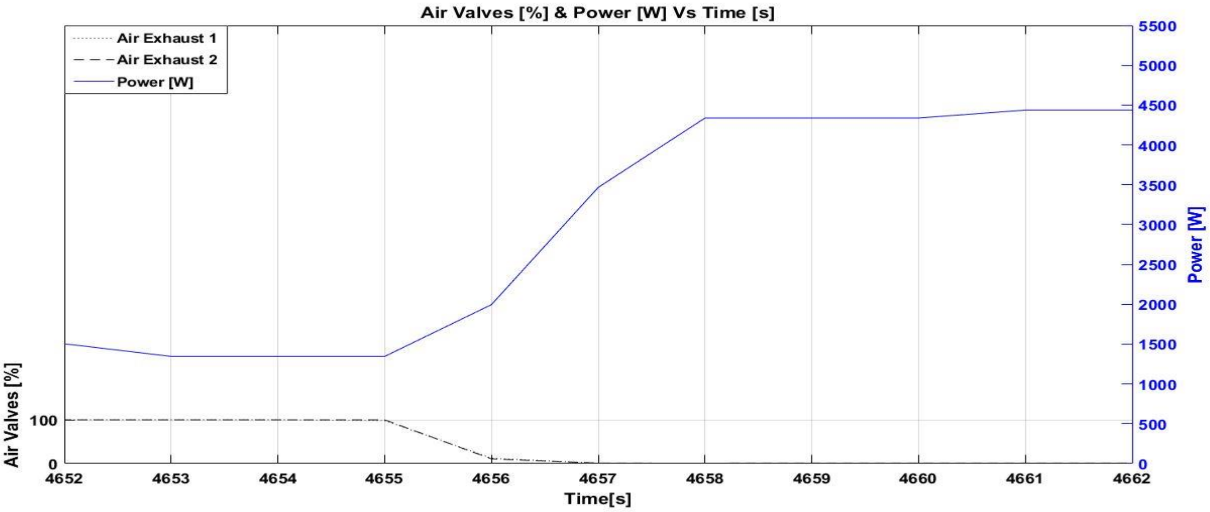


Figure 26 A chosen time interval (4652s-4662s) while closing both power air valves for higher power peak-shaving

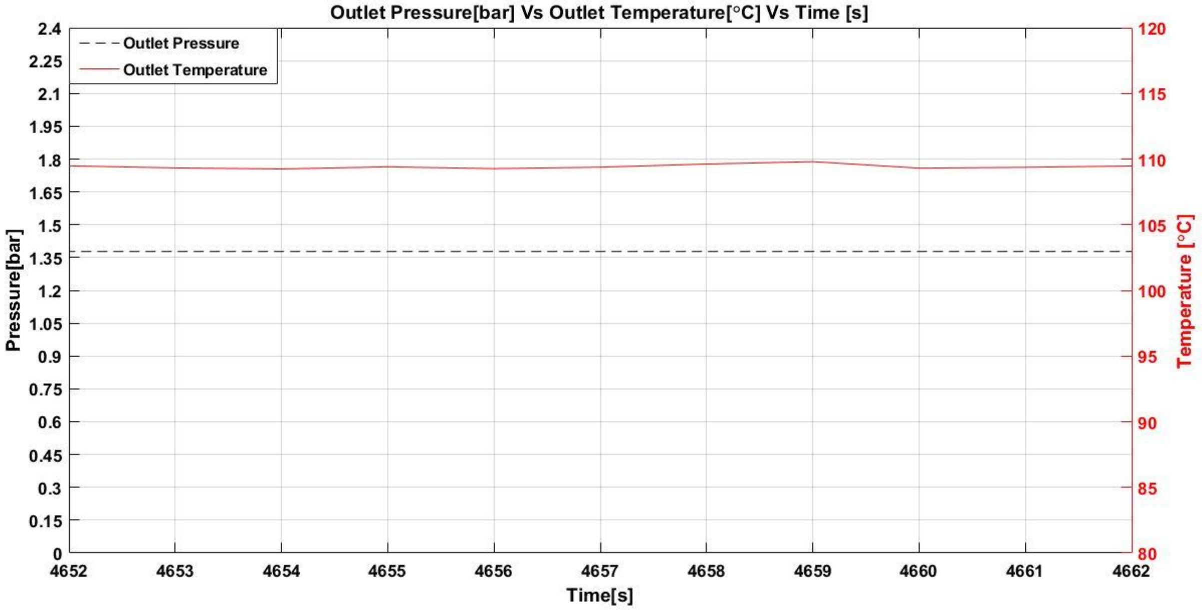
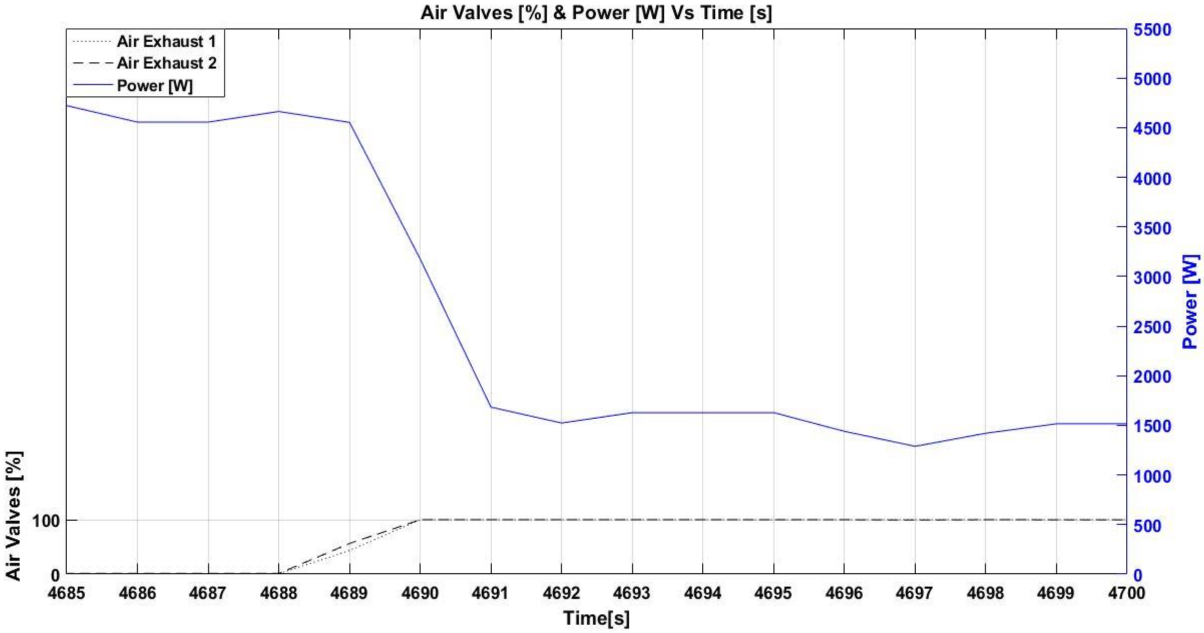


Figure 27 The outlet steam pressure and temperature at the interval (4652s-4662s)

As shown in Figure 28, the power valves 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 29 shows that the pressure and temperature of the outlet steam at the given interval are still constant as previous.



igure 28 A chosen time interval (4685s-4700s) while opening both power air valves for higher power peak-shaving

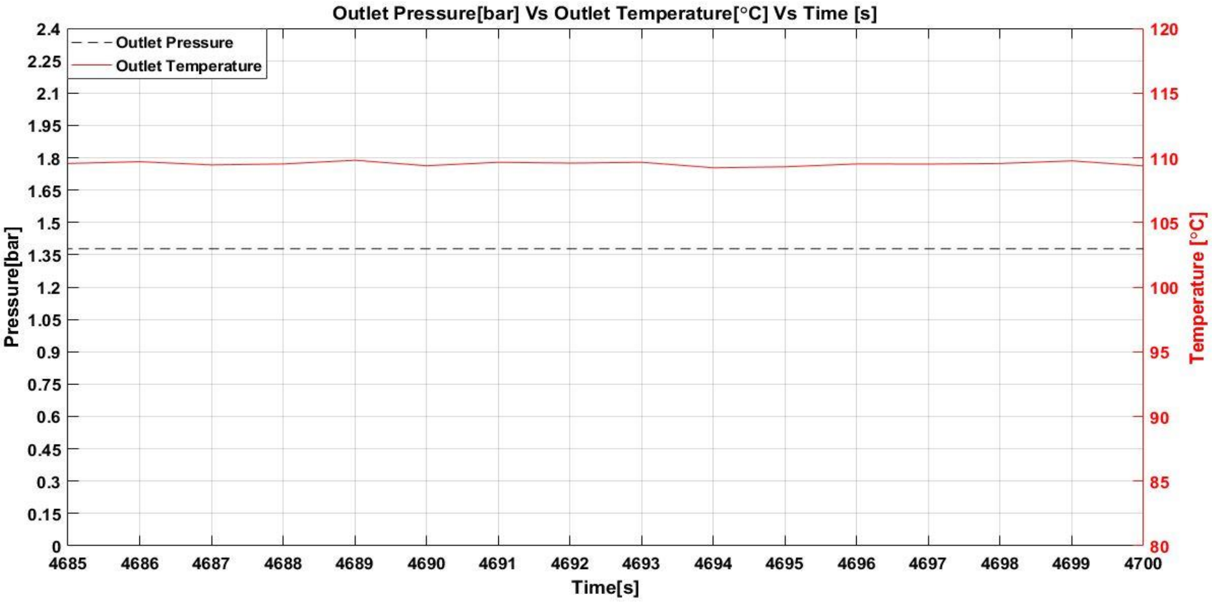


Figure 29 The outlet steam pressure and temperature at the interval (4685s-4700s)

5.1.4 Power Validation

For the RCG add-on cycle, the consumed power of the air compressor should be equal to the generated power of the steam turbine in a steady-state. Thus, the boundaries have been set along the RCG add-on cycle as seen in Figure 30. The power output is calculated for both the compressor and steam turbine to validate that they should be equal.

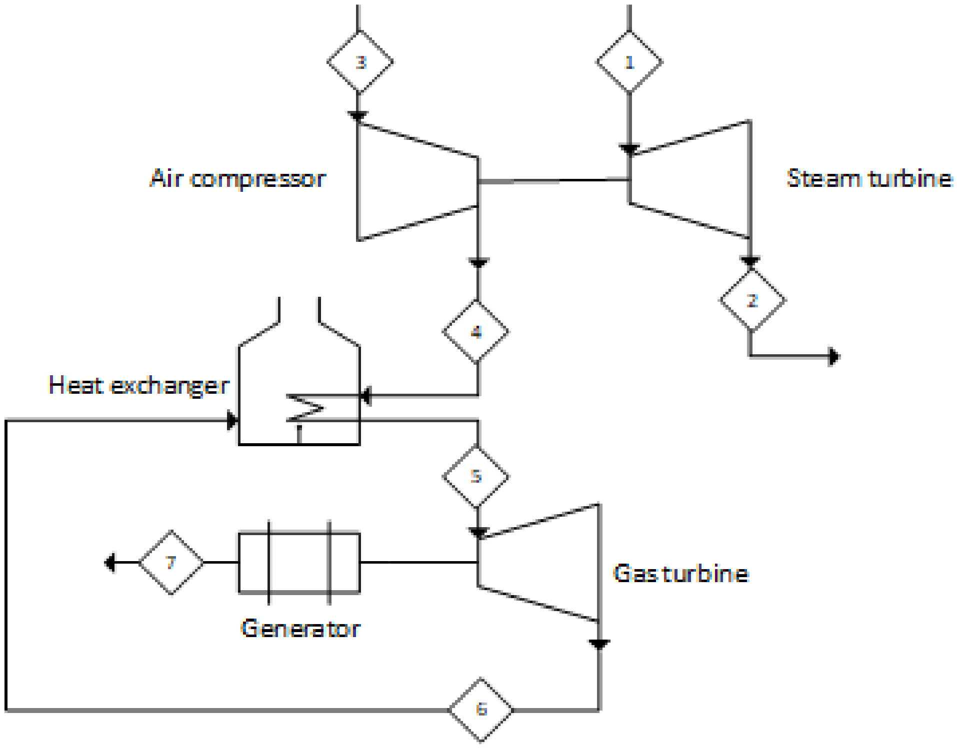


Figure 30 The RCG add-on boundaries

It can be shown also that the steam turbine only runs the compressor and that's the reason why the power of both of them is equal:

$$P_{st}[kW] = P_c[kW] \tag{1}$$

Where P_{st} is the power of the steam turbine in kW and P_c is the consumed power of the compressor in kW.

In the steam turbine, the steam stream 1 is coming from the factory with a high pressure. This energy transforms into the turbine in terms of shaft power which drives the air compressor. After this expansion of steam, it returns back to the factory with the required specifications which does not affect the steam conditions. This is ideally an isentropic process which can be explained by this equation:

$$P_{st} = \dot{m}_{st}(h_1 - h_{2s}) \tag{2}$$

Where P_{st} is the power output of the steam turbine in kW, $\dot{m}_{st}$ is the mass flow rate of the steam in kg/s, h_1 is the enthalpy in kJ/kg of the inlet steam for streamline 1 and h_{2s} is the hypothetical steam enthalpy in kJ/kg at the outlet steam streamline 2.

However, there should be an isentropic efficiency added to the equation as the turbine does not ideally have an isentropic expansion in reality. The more efficient the turbine, the closer it can be considered isentropic expansion. So, the real power output from the steam turbine can be calculated with this equation:

$$P_{st} = \eta_{st}\eta_{mech}\dot{m}_{st}c_{P,st}(T_1 - T_2) \tag{3}$$

Where η_{st} is the isentropic efficiency of the steam turbine, η_{mech} is the mechanical efficiency of the steam turbine, $c_{P,st}$ is the steam specific heat in kJ/kg.K at constant pressure, the steam properties are available in many databases, T_1 is the inlet steam temperature in K and T_2 is the outlet steam temperature in K.

The steam turbine is shaft connected to the air compressor which is another essential component of the RCG add-on cycle. It takes the ambient air from the surrounding then compresses it to the required pressure that is used for the power cycle. The power output of the air compressor can be ideally calculated using the following equation:

$$P_c = \dot{m}_a(h_3 - h_{4s}) \tag{4}$$

Where P_c is the power of the compressor in kW, $\dot{m}_a$ is the mass flow rate of the air in kg/s, h_3 is the enthalpy of air in streamline 3 in kJ/kg and h_{4s} is the hypothetical air enthalpy in streamline 4 in kJ/kg assuming that the compression is isentropic.

In reality, the compressor cannot be ideally perform in an isentropic process like the same case of the steam turbine. So, an isentropic efficiency should be added to the compressor power equation and the two new equation can be formed:

$$P_C = \frac{\dot{m}_a(h_3 - h_{4s})}{\eta_C} \tag{5}$$

$$P_C = \frac{\dot{m}_a\, c_{P,a}(T_3 - T_{4s})}{\eta_C} \tag{6}$$

Where η_c is the isentropic efficiency of the compressor, $c_{P,a}$ is the air specific heat in kJ/kg.K at constant pressure, T_3 is the air temperature in streamline 3 in K and T_{4s} is the hypothetical air temperature in streamline 4 in K. By assuming that the air behaves as an ideal gas, a relation between the consumed power of the compressor with the pressure ration and the air mass flow rate:

$$P_C = \frac{\dot{m}_a\, c_{P,a}T_3\left((\frac{P_4}{P_3})^{\frac{\gamma-1}{\gamma}} - 1\right)}{\eta_C} \tag{7}$$

Where P_4 is the pressure of air in bar in streamline 4, P_3 is the air pressure in bar in streamline 3 and γ is the specific heat ratio which is the division of specific heat at constant pressure to specific heat at constant volume.

Two different points from the experiment have been chosen to validate the previous illustration that the power of the steam turbine should be equal to the compressor. One point from the lower peak-shaving stage and the other from the higher peak-shaving stage. Table 2 shows the parameters at the two points for calculating the power output:

Table 2 Parameters of the chosen two points from low and high peak-shaving stages

	Point #1	**Point #2**
Steam Turbine	Angular Velocity = 2750 RPM η_{mech}= 85 % η_{st} = 30% T_{in} =155°C T_{out} =109°C Cp =2.49 (steam tables) $\dot{m}_{st}$ = 0.108 kg/s	Angular Velocity = 4750 RPM η_{mech}= 85 % η_{st} = 30% T_{in} =170°C T_{out} =109°C Cp =2.8 (steam tables) $\dot{m}_{st}$ = 0.12 kg/s
Compressor	Angular Velocity = 10000 RPM $\dot{m}_{air}$ = 0.25 kg/s (compressor map) T_a =30°C Cp =1 γ =1.4 r =1.1 (pressure ratio) η_c = 70%	Angular Velocity = 19500 RPM $\dot{m}_{air}$ = 0.425 kg/s (compressor map) T_a =30°C Cp =1 γ =1.4 r =1.1 (pressure ratio) η_c = 70%

Thus, the power outputs of the compressor and steam turbine are calculated using the power equations (3) and (7) respectively. For point #1, the calculated steam power output is 3.15 kWe while for the compressor power output is 2.98 kWe. For point #2, the calculated steam power output is 5.22 kWe while for the compressor power output is 5.07 kWe. As it is seen, there is a slight difference in the power calculations of up to 5% which is due to the transmission and the heat losses in the system.

5.1.5 Time Scale

There is another method that can be used to confirm the transient time response of the RCG add-on. It is by measuring the time taken for emptying the whole RCG add-on system with air. A specific point is chosen while both air valves are closed and the system is generating the maximum power output of the 4.8 kWe. The used parameters are in the following Table 3:

Table 3 Specifications of air and dimensions of the pipes and heat exchanger

	Compressor	**Pipes**	**Heat exchanger**
Parameters	- Intlet air pressure= 1 bar - Intlet air temperature = 30 °C - Outlet air pressure = 1.1 bar - Outlet air temperature = 43.2 °C - Heat capacity ratio = 1.4	- Diameter = 0.1 m - Length = 2.5 m	- Area outside the steam tube = 0.536 m^2 - Length = 1.562 m

First, the isentropic efficiency of the compressor is calculated by using the following equation:

$$\eta_c = \frac{T_3}{T_4 - T_3}\left((\frac{P_4}{P_3})^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{8}$$

The calculated efficiency is around 63% for the compressor. As from the compressor map, the corrected air flow rate is 0.4 m^3/s which is equal to 0.49 kg/s. and the normal air mass flow rate should be calculated by using this equation:

$$Normal\ \dot{m} = corrected\ \dot{m}\ \frac{\frac{P_4}{P_{ref}}}{\sqrt{\frac{T_4}{T_{ref}}}} \tag{9}$$

In which T_{ref} = 30 °C and P_{ref} = 1 bar. The calculated normal mass flow rate of air is 0.44 kg/s.

Thus, the filling-and-emptying time can be calculated by these equations:

$$v = \pi r^2 L \tag{10}$$

$$M = v\,\rho \tag{11}$$

$$t = \frac{M}{\dot{m}} \tag{12}$$

Where v is the volume (m^3), M is the mass of the air (kg), ρ is the air density (kg/m^3) and $\dot{m}$ is the mass flow rate of air (kg/s), and t is the time (s).

For piping, the diameter of the pipes is 0.1 m and the length from the compressor to the power turbine is 2.5 m. So, the volume is calculated to be 0.0196 m^3 and the density of air is 1.22 kg/m^3. So that the mass of air inside is around 0.024 kg.

For the heat exchanger, the volume and mass are calculated and they are 0.84m^3 and 1.03kg respectively. Finally, the sum of all masses in total is 1.05 kg and the mass flow rate is 0.44kg/s.

The calculated filling up and emptying time is almost 2.4 seconds. This result relatively confirms the obtained results from the previous experimental section of the RCG add-on operation at HIS factory. It is concluded that the time scale of the RCG add-on system is depending on two parameters which can be developed in the future; valve response time and filling and emptying volume. The response timing of the valves depends on the mechanical properties of the valves which can be replaced by faster valves for a better response. The change of the volume of the heat exchanger and the piping can have an impact on the filling and emptying time. While the speed of the steam turbine and respectively the compressor remains constant when the RCG add-on is in operation.

The choice of the chosen time intervals at different power output in the lower and higher peak-shaving stages is to measure and validate the time response for peak-shaving fluctuations. It has been concluded that the supply for the peak-shaving demand can be obtained in very rapid response in a range of up to 4 seconds. This has not been seen in any solid fuel fired boiler system. If required, the time response can be enhanced for a more rapid response by optimizing the two mentioned parameters.

6 Economic assessment of the RCG add-on system

A feasibility study is conducted for the commercial scale of the RCG add-on system. First, the setup of the commercial scale is identified. Then, the capital cost (CAPEX) and operating expenditure (OPEX) are illustrated and investigated through economic calculations.

6.1 RCG commercial-scale composition

A 5 kWe RCG add-on prototype has been experimentally investigated in this thesis. However, there is a future plan of upgrading it to 40 kWe until reaching the commercial scale of 120 kWe. For upscaling the RCG add-on system, the same technology and equipment of the 5 kWe RCG add-on are used. However, the number of components varies according to the needed power output. This should be further investigated. Mainly, the used steam turbine can support the system up to 360 kWe. Thus, the change is mainly in the number of power turbines set and compressors.

The RCG add-on system composition depends mainly on off-the-shelf equipment that is available in the market. However, the heat exchanger has different designs depending on the project. The further investigation includes two scenarios of the RCG add-on for power outputs of 120kWe, 240kWe, and 360kWe.

The targeted market is small and medium-sized enterprises (SMEs) where there are existing industrial steam systems using biomass as a fuel. The proposed system focuses on cogeneration applications for producing heat and electricity for a power range of 100 kW and 2 MW. The facilities should have already an industrial steam boiler where they generate steam with different pressures for the use of their own processes. There are many industries that have these requirements, such as the processing of food, wood, and other beverages [7].

6.2 Cost & savings estimation

Two main parts should be considered to have an overall estimation of the total cost of the RCG add-on: CAPEX and OPEX. The cost of the used equipment and installation is CAPEX. The maintenance and fuel cost is OPEX.

The total capital investment of the RCG add-on system could be reduced due to the advantage of proposing it as an add-on to an existing steam system. Also, this is a more feasible solution for small scale industries where they demand a decentralized cheaper electricity generation system compared to the grid. Also, the system allows a better fuel consumption which is environmentally friendly. The main feature of the system is the free-acting power turbine which allows the possibility of decoupling of the steam and electricity production. This also allows the rapid response of the power turbine for electrical peak-shaving. The RCG add-on is compatible to work with multiple types of fuel, but the company focuses mainly on the utilization of renewable resources such as waste and biofuel.

Market research has been done to determine the cost values for each component of the commercial RCG add-on setup. The prices can vary accordingly to the number of ordered components, and it can be further investigated deeply to reach more suppliers for these components. Moreover, a profit margin for the company is set to be 15% of the total cost.

Table 4 shows the CAPEX of the RCG add-on system by component [25]. Additionally, the total summation of all costs and the marginal profit are shown at the bottom of the table. Three columns show all the suggested scenarios and the associated costs and profit for that.

Table 4 CAPEX of the RCG add-on commercial system

Components	120kWe	240kWe	360kWe
Compressor	€ 14,000.00	€ 28,000.00	**€ 42,000.00**
Heat exchanger	€ 100,000.00	€ 180,000.00	**€ 250,000.00**
Steam turbine	€ 85,000.00	€ 85,000.00	**€ 85,000.00**
Gas turbine	€ 6,400.00	€ 12,800.00	**€ 19,200.00**
Generator	€ 20,000.00	€ 40,000.00	**€ 60,000.00**
Instrumentation	€ 16,700.00	€ 22,400.00	**€ 28,100.00**
Skid	€ 10,000.00	€ 20,000.00	**€ 30,000.00**
Pipes + insulation	€ 20,000.00	€ 40,000.00	**€ 60,000.00**
General parts (shafts, belts, bearings…etc.)	€ 5,000.00	€ 10,000.00	**€ 15,000.00**
Valves	€ 24,600.00	€ 36,900.00	**€ 55,300.00**
Power electronics	€ 20,000.00	€ 40,000.00	**€ 60,000.00**
Electric cabinet	€ 10,000.00	€ 20,000.00	**€ 30,000.00**
Engineering + assembly	€ 40,000.00	€ 40,000.00	**€ 40,000.00**
Intercooler	€ 2,000.00	€ 4,000.00	**€ 6,000.00**
Profit margin	€ 64,000.00	€ 100,300.00	**€ 136,500.00**
Total	**€ 437,700.00**	**€ 679,400.00**	**€ 917,100.00**

It is seen from the table of CAPEX that there are some components that have a significant portion of the total cost, such as the heat exchanger and the steam turbine. Thus, further research for suppliers of these two components to get lower prices affects the total cost of the RCG add-on.

The OPEX can be categorized into two main parts: the maintenance cost and the fuel cost. For the maintenance cost, it can be estimated as no RCG add-on system has been running for a long time. Thus, it can be referenced to the maintenance cost values of typical steam turbines. Usually, the maintenance cost separately of steam turbine and gas turbine in a cogeneration system is around 0.01 €/kWh [4]. Second, the extra fuel cost may be required to generate the same heat demand while operating the RCG add-on. The most preferred fuel for the RCG add-on from the environmentally perspective is biomass. The price ranges in Europe from 4.15 €/GJ to 9.5 €/GJ depending on the source such as agriculture residues or imported wood pellets, respectively [26]. As a price reference, the average price is taken to be 7.00 €/GJ.

The industrial electricity prices vary around Europe. RCG add-on can generate some money saved for the industrial organizations in these countries which suffer from high electricity prices. According to Eurostat statistics that has been done in the second half of 2018 for the industrial electricity prices in each country in Europe [24], some countries have really higher prices compared to others. This is seen in Figure 31. The values in the graph do not consider the subsidies in some countries, which lead to decreasing electricity prices. It is seen that Cyprus, Germany, Italy, and the UK are the top four countries, including taxes. The price ranges from 0.058 €/kWh (the lowest) in Georgia to 0.18 €/kWh in Cyprus (the highest) [24]. Thus, the company has decided to consider Germany as our targeted market because it is one of the top four countries with high industrial electricity prices, in addition, it is geographically near to Heat Power BV Company which is based in Eindhoven, the Netherlands. As a reference, the industrial electricity cost in Germany is 0.15 €/kWh.

Figure 31 The industrial electricity prices across the EU extracted from Eurostat [24]

6.3 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 system lifetime period is estimated to be 20 years. The calculations and analysis of the RCG add-on system using these parameters are explained in this subsection.

First, the calculation of the payback time has been done. This meant to show the period that is taken for the RCG add-on system to return back all the investment. The OPEX and revenue are subjected to change yearly due to the inflation rate, which is set to be 1.5% yearly. So, the payback time is calculated by the following equation:

$$Payback\ period, years = \frac{Investment}{Net\ annual\ cash\ flow} \tag{13}$$

Second, the calculation of the net present value (NPV) has been done. It is mainly to show the present value of the system by summation of cash flow for a given time period which is 20 years for the RCG add-on system. A discount rate is used for the calculation, which is the investment return that could be earned from other alternatives. So, the positive result of the NPV indicated that the project is profitable, but the negative result indicates that the project is not profitable. This evaluates the profitability of the system with different options of investment to make it easier for the decision-makers to make a proper decision. The NPV equation is as follows:

$$NPV = -CAPEX + \sum_{t=1}^{n} \frac{(net\ cash\ flow)_t}{(1+i)^t} \tag{14}$$

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

Third, the calculation of the Internal Rate of Return (IRR) has been done to estimate the attractiveness of the RCG add-on project. The output of this calculation is the discounted rate in which the NPV is equal to zero. So, if the resulted IRR falls above the project required rate of return then this project is desirable. However, if it is below the required rate of return, the project should not be considered. Thus, the IRR equation is as follows:

$$0 = -CAPEX + \sum_{t=1}^{n} \frac{(net\ cash\ flow)_t}{(1+i)^t} \tag{15}$$

Finally, the calculation of the Levelized Cost of Electricity (LCOE) has been done to evaluate the cost and electricity production of the RCG add-on through the system's lifetime. This method has been widely used by many international energy organizations such as the International Renewable Energy Agency (IRENA).

As it is an economic measuring tool that allows the comparison of different electricity generation system with the unit cost per kWh or MWh. Mainly, it depends on the summation of the total cost of the power generation system through its lifetime divided by the energy produced over the lifetime of the system. This is seen in the following equation:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{(Fuel\ and\ Maintenace\ cost)_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{(Energy\ produced)_t}{(1+i)^t}} \tag{16}$$

Some assumptions have been stated as shown in Table 5 and the results of the calculations are shown in Table 6.

Table 5 Some assumptions for the calculations

Fuel cost	7 €/GJ or 0.025 €/kWh
Inflation rate	1.5 %
Discount rate	10 %
Electricity price	0.15 €/kWh
Operating time hours/year	2160 hours/year
Capacity factor	90 %
A lifetime of the RCG add-on system	20 years

Table 6 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 from the previous results 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 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.

The LCOE results are compared with the industrial electricity prices from the utilities across Europe, as it does not depend on the electricity price. According to Figure 17, the highest LCOE of the 120kWe RCG add-on which is 0.092 €/kWh is relatively compared to the average price of the whole European countries.

It is noted that the CAPEX of the RCG add-on does not vary much since most of suppliers of the components are the same for the European countries. Thus, the variation in the LCOE is caused by the cost of fuel and maintenance of range up to 50 % from a country to another.

To sum up, there are two conclusions which are established in this feasibility study. First, the optimum design and fabrication of the RCG add-on system should avoid as much as possible the mechanical and heat losses throughout the whole system. Thus, the RCG add-on can have an increase in the efficiency. This directly leads to reducing the amount of fuel used and consequently the cost that impacts the LCOE. Additionally, the cost of the generated electricity from the RCG system can also be decreased if the prices of the fuel is decreased. This illustrates how the cost of fuel is a vital component of the RCG system.

7 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 5 kWe 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, 20 year of lifetime of the RCG add-on system.

Some future considerations aim to develop the RCG technology in potential:

- A plan has been set to up-scale the RCG add-on to 40 kWe system. Additionally, there will be an additional superheater installed for the RCG add-on cycle. This increases the performance of the new system to avoid the saturation of the steam that causes problems for the system components.
- The implementation of the 40 kWe RCG add-on at HIS and repeat the same experimental studies as for the 5 kWe. The future plan is to keep upgrading the system at HIS until reaching the commercial scale of 120 kWe.
- The technical and feasible investigation of the RCG as a stand-alone system for a high loads power plant.

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9 Appendix A: Compressor and Power Turbine RPM

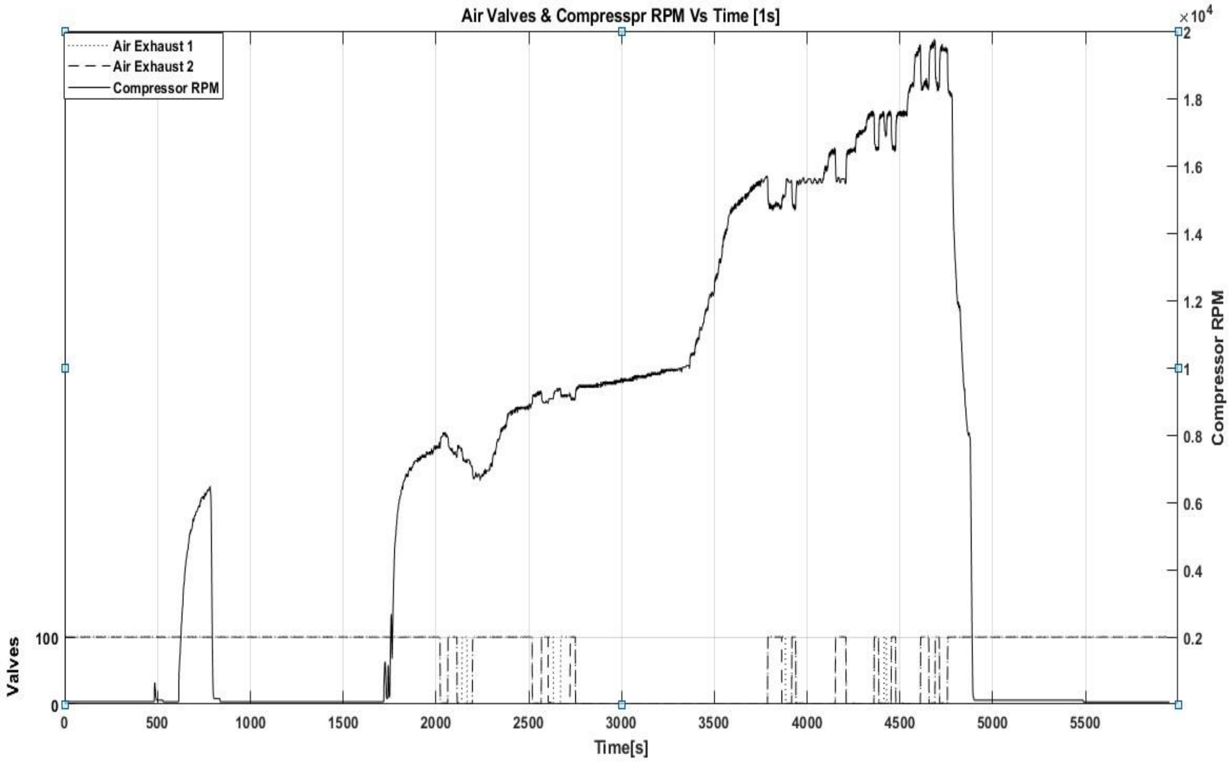


Figure 32 The change in air valves settings along with the Compressor RPM

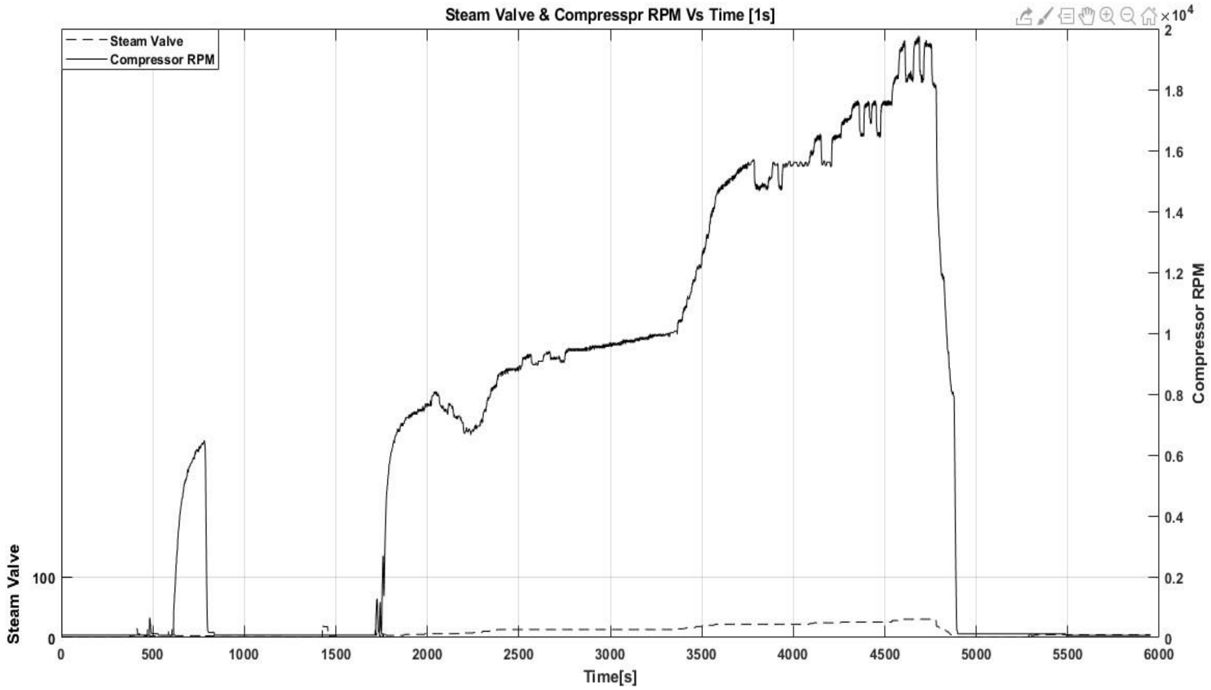


Figure 33 The gradual opening of steam valve along with the Compressor RPM

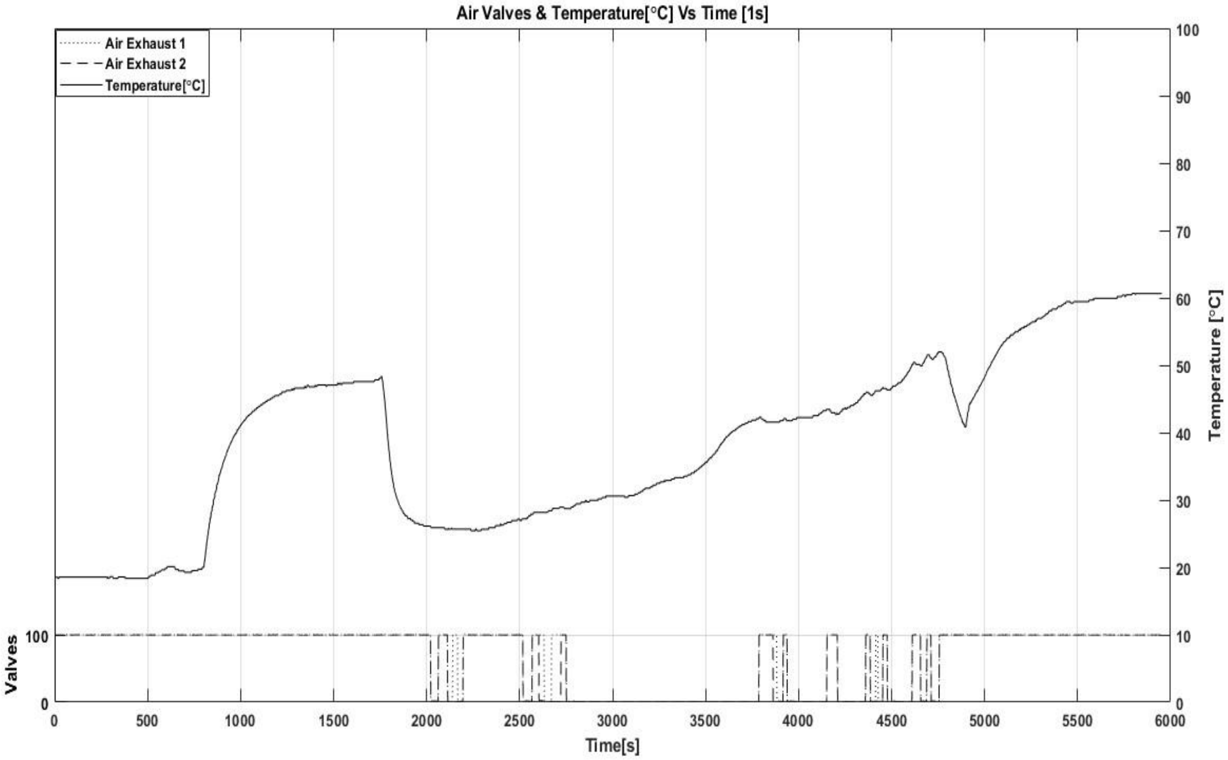


Figure 34 The compressed air temperature along with the change in air valves settings

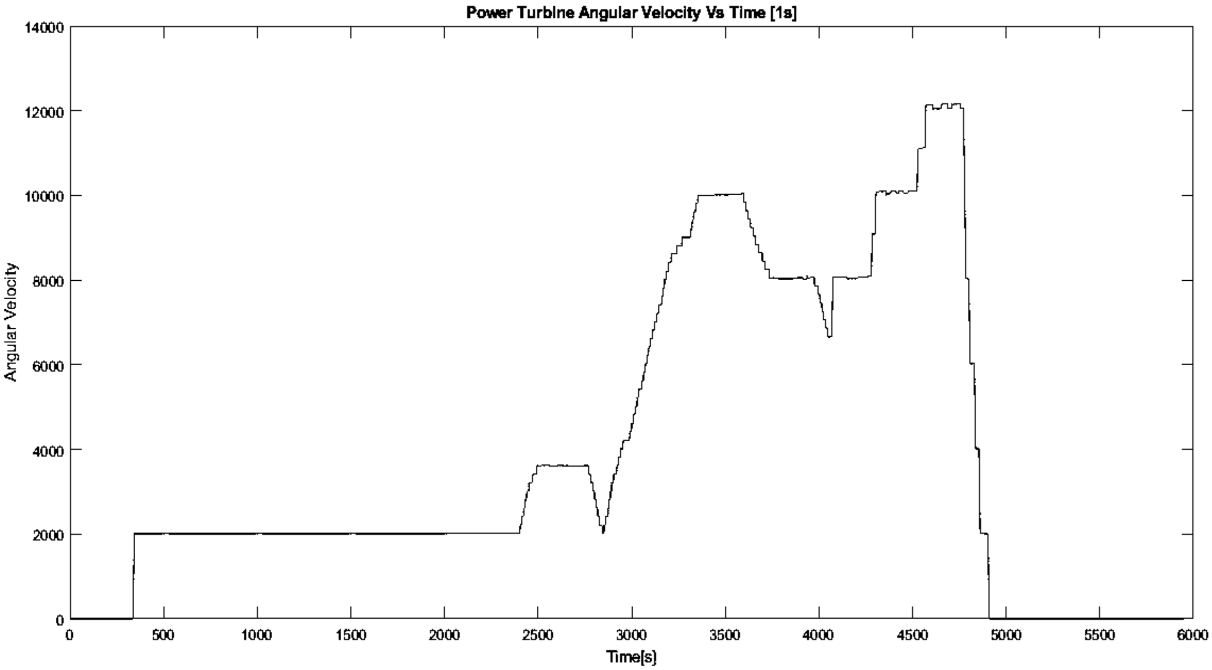
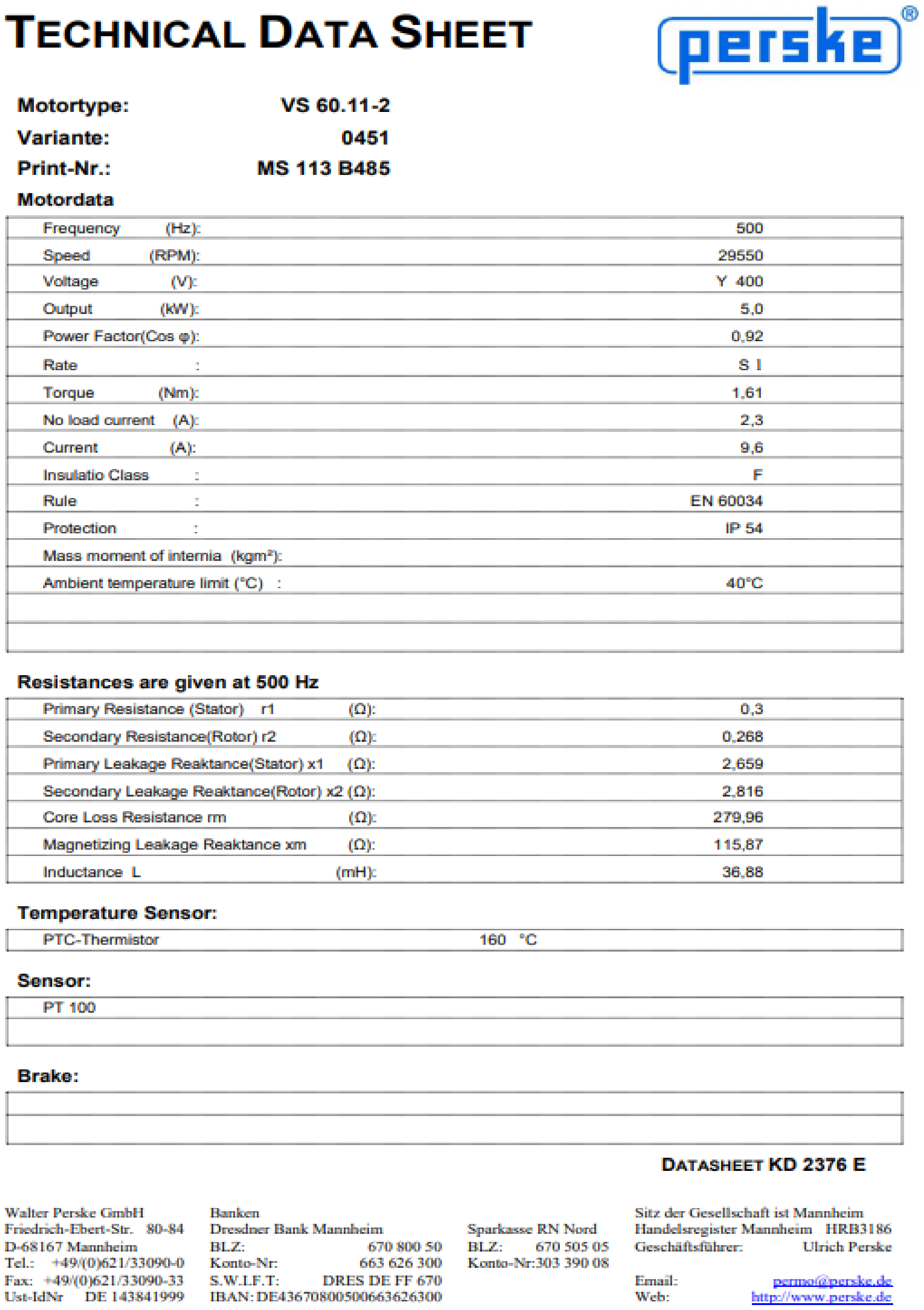


Figure 35 The power turbine angular velocity

10 Appendix B: Technical datasheet generator, pressure and temperature sensors

Electrical generator



TECHNICAL DATA SHEET

perske®

Motortype:	**VS 60.11-2**
Variante:	**0451**
Print-Nr.:	**MS 113 B485**

Motordata

Frequency (Hz):	500
Speed (RPM):	29550
Voltage (V):	Y 400
Output (kW):	5,0
Power Factor(Cos φ):	0,92
Rate :	S 1
Torque (Nm):	1,61
No load current (A):	2,3
Current (A):	9,6
Insulatio Class :	F
Rule :	EN 60034
Protection :	IP 54
Mass moment of internia (kgm²):	
Ambient temperature limit (°C) :	40°C

Resistances are given at 500 Hz

Primary Resistance (Stator) r1	(Ω):	0,3
Secondary Resistance(Rotor) r2	(Ω):	0,268
Primary Leakage Reaktance(Stator) x1	(Ω):	2,659
Secondary Leakage Reaktance(Rotor) x2	(Ω):	2,816
Core Loss Resistance rm	(Ω):	279,96
Magnetizing Leakage Reaktance xm	(Ω):	115,87
Inductance L	(mH):	36,88

Temperature Sensor:

PTC-Thermistor	160 °C

Sensor:

PT 100

Brake:

DATASHEET KD 2376 E

Walter Perske GmbH
Friedrich-Ebert-Str. 80-84
D-68167 Mannheim
Tel.: +49/(0)621/33090-0
Fax: +49/(0)621/33090-33
Ust-IdNr DE 143841999

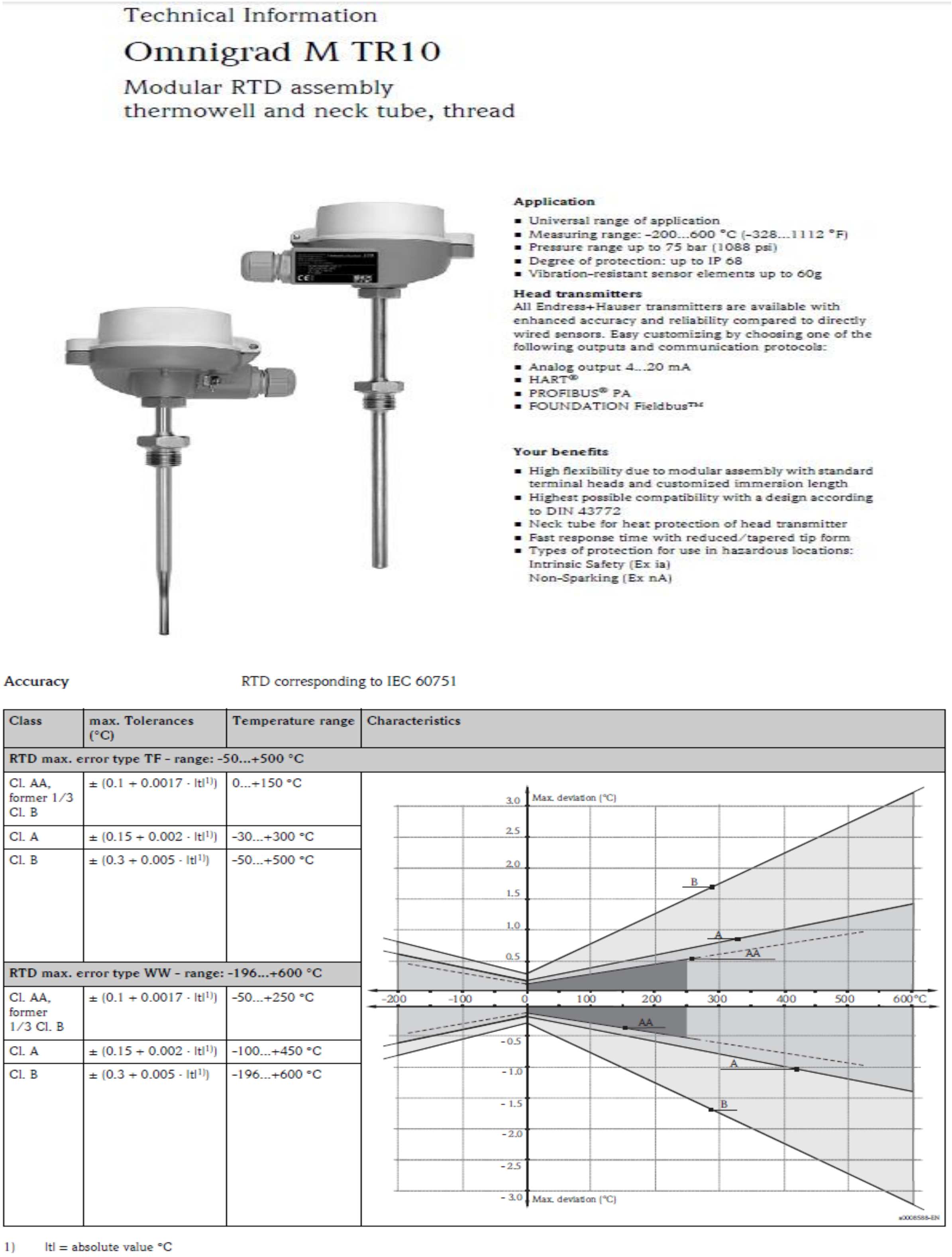
Banken
Dresdner Bank Mannheim
BLZ: 670 800 50
Konto-Nr: 663 626 300
S.W.I.F.T: DRES DE FF 670
IBAN: DE43670800500663626300

Sparkasse RN Nord
BLZ: 670 505 05
Konto-Nr:303 390 08

Sitz der Gesellschaft ist Mannheim
Handelsregister Mannheim HRB3186
Geschäftsführer: Ulrich Perske

Email: permo@perske.de
Web: http://www.perske.de

Temperature Sensor



Technical Information

Omnigrad M TR10

Modular RTD assembly
thermowell and neck tube, thread

Application

- Universal range of application
- Measuring range: -200...600 °C (-328...1112 °F)
- Pressure range up to 75 bar (1088 psi)
- Degree of protection: up to IP 68
- Vibration-resistant sensor elements up to 60g

Head transmitters

All Endress+Hauser transmitters are available with enhanced accuracy and reliability compared to directly wired sensors. Easy customizing by choosing one of the following outputs and communication protocols:

- Analog output 4...20 mA
- HART®
- PROFIBUS® PA
- FOUNDATION Fieldbus™

Your benefits

- High flexibility due to modular assembly with standard terminal heads and customized immersion length
- Highest possible compatibility with a design according to DIN 43772
- Neck tube for heat protection of head transmitter
- Fast response time with reduced/tapered tip form
- Types of protection for use in hazardous locations: Intrinsic Safety (Ex ia) Non-Sparking (Ex nA)

Accuracy RTD corresponding to IEC 60751

Class	max. Tolerances (°C)	Temperature range	Characteristics
RTD max. error type TF - range: -50...+500 °C			
Cl. AA, former 1/3 Cl. B	± (0.1 + 0.0017 · |t|1))	0...+150 °C	
Cl. A	± (0.15 + 0.002 · |t|1))	-30...+300 °C	
Cl. B	± (0.3 + 0.005 · |t|1))	-50...+500 °C	
RTD max. error type WW - range: -196...+600 °C			
Cl. AA, former 1/3 Cl. B	± (0.1 + 0.0017 · |t|1))	-50...+250 °C	
Cl. A	± (0.15 + 0.002 · |t|1))	-100...+450 °C	
Cl. B	± (0.3 + 0.005 · |t|1))	-196...+600 °C	

1) |t| = absolute value °C

Pressure Sensor

JUMO MIDAS SI
OEM-Pressure Transmitter

Brief description

This pressure transmitter can be used for measuring the relative (gauge) and absolute pressures in liquids and gases. The pressure transmitter operates on the piezoresistive measuring principle. The pressure is converted into an electrical signal.

Type 401006/000-xxx-xxx-xxx-20-61

Technical data

Reference conditions
to DIN 16 086 and IEC 770/5.3

Measurement ranges
see Order details

Overload limit
for ranges up to
0 — 25 bar 3 x full scale

Bursting pressure
for ranges up to
0 — 25 bar ≤ 4 x full scale

Parts in contact with medium
standard: stainless steel, Mat. Ref. 1.4571, 1.4435

Output

4 — 20 mA 2-wire	burden ≤ (U_B-10 V) / 0.02A
0.5 — 4.5 V	burden ≥ 20 kΩ
1 — (5)6 V	burden ≥ 10 kΩ
0 — 10 V	burden ≥ 10 kΩ

Burden error
< 0.5% max.

Zero signal deviation
≤ 0.3% of full scale

Thermal hysteresis
≤ ± 0.5% of full scale
(within compensated temperature range)
≤ ± 1% for ranges 0 — 250 mbar
0 — 400 mbar
0 — 600 mbar

Ambient temperature error
within range -20 to +85°C
(compensated temperature range)
zero: ≤ 0.02%/°C typical,
≤ 0.04%/°C max.

Deviation from characteristic
≤ 0.5% of full scale
(limit point adjustment)

Hysteresis
≤ 0.1% of full scale

Repeatability
≤ 0.05% of full scale

Response time
≤ 3 msec max.

Stability over 1 year
≤ 1% of full scale

Supply

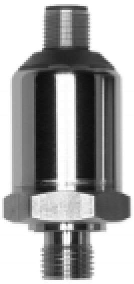
10 — 30 V DC	(for output 4 — 20 mA and 1 — (5)6 V)
5 V DC	(for output 0.5 — 4.5 V)
11.5 — 30 V DC	(for output 0 — 10 V)

Ripple: the voltage spikes must not go outside the limits specified for the supply.
Max. current drawn: approx. 25 mA

Supply voltage error
≤ 0.02% per V
(nominal supply voltage 24 V DC)
ratiometric with supply 5 V DC (±0.5 V)

Permissible ambient temperature
for version with connector:
-20 to +125°C
for version with attached cable:
-20 to +100°C

Storage temperature
-40 to +125°C
for version with attached cable
-20 to +100°C



Type 401006/000-xxx-xxx-xxx-20-36

Permissible temperature of medium
-30 to +125°C

Electromagnetic compatibility (EMC)
to EN 61 326

Mechanical shock
(to IEC 68-2-27)
100 g/1 msec

Mechanical vibration
(to IEC 68-2-6)
20 g max. at 15 — 2000 Hz

11 Appendix C: KKK steam turbine characteristics & Compressor Map

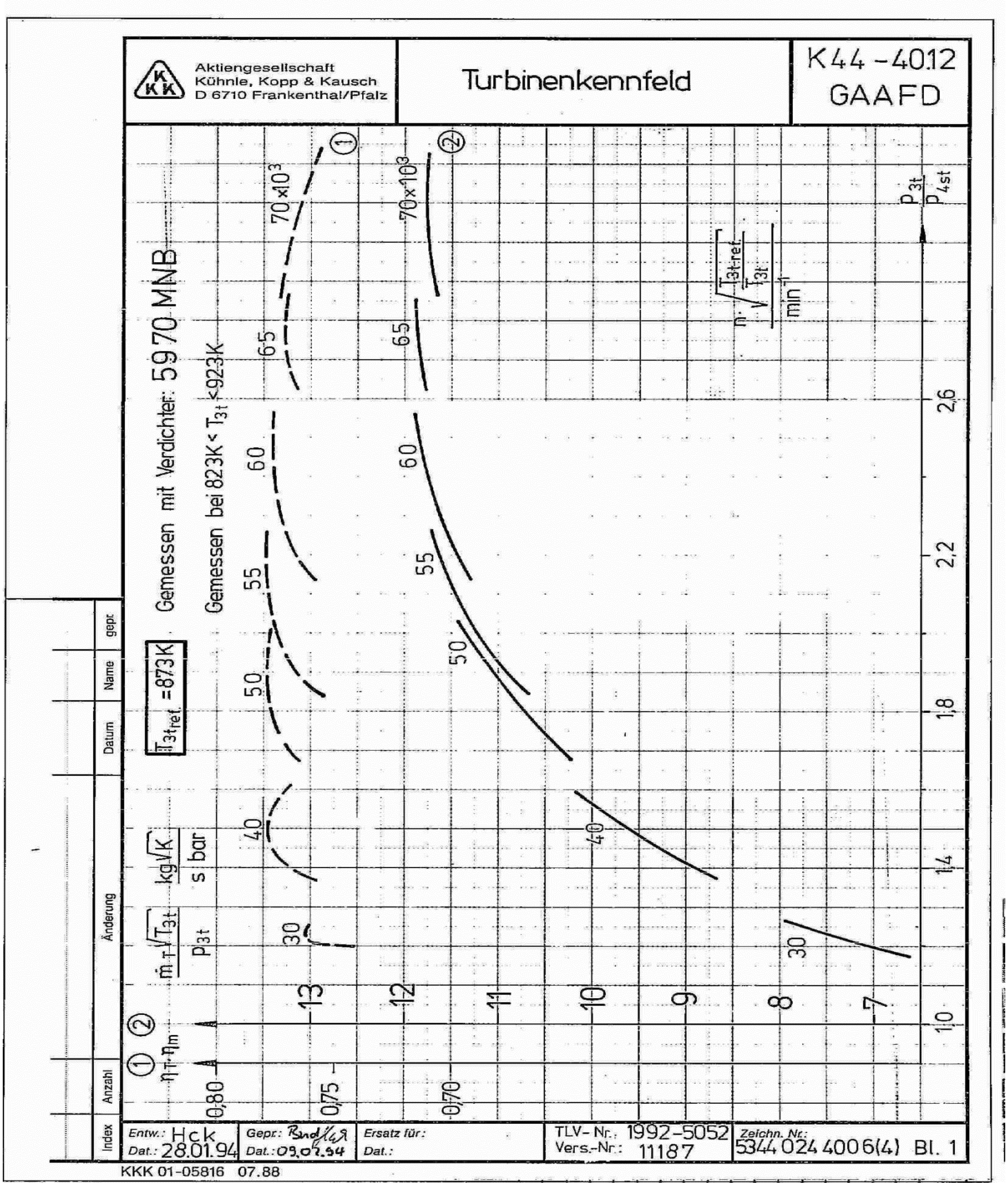


Figure 36 Steam turbine map

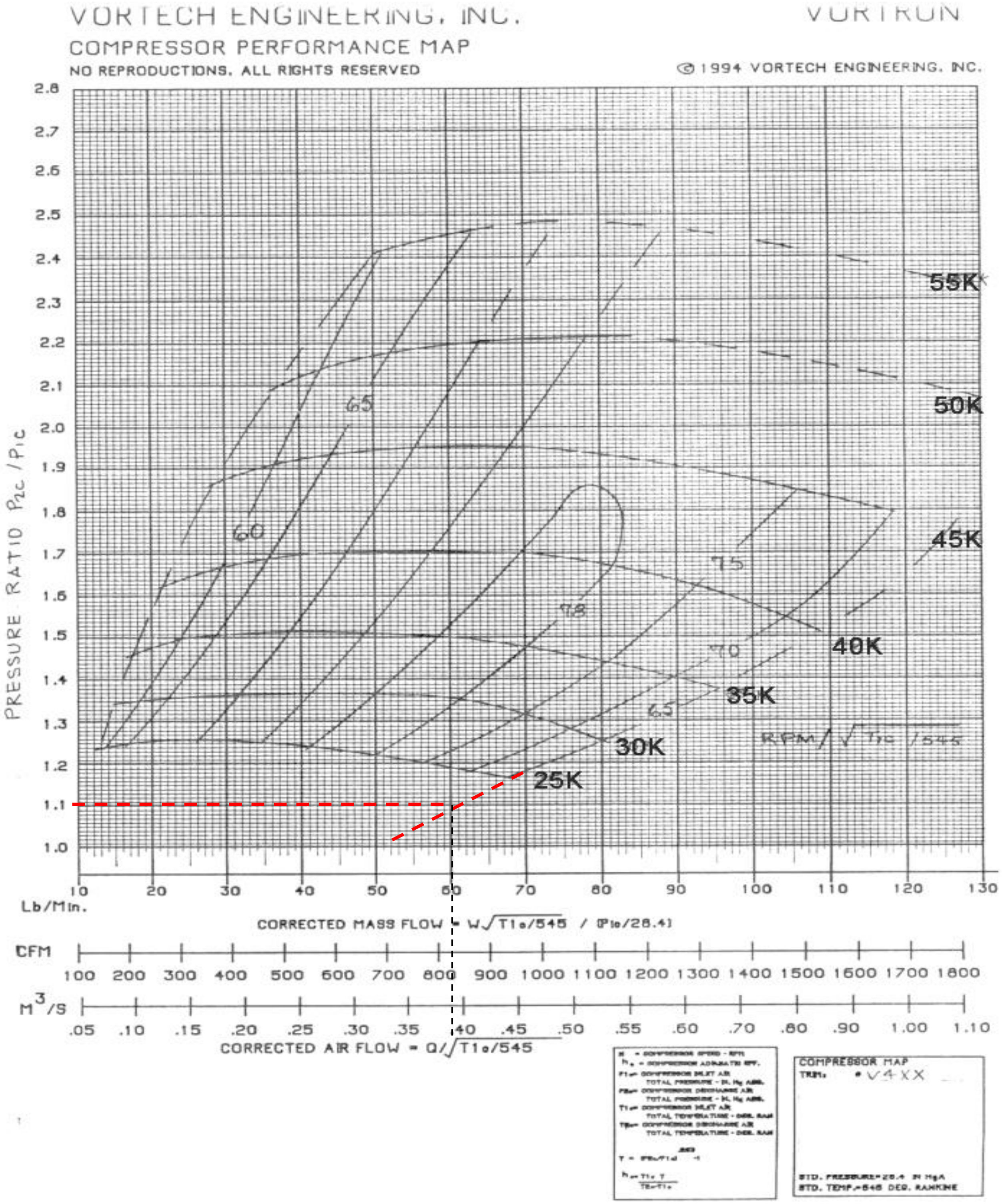


Figure 37 Compressor map

12 Appendix D: Power calculation reference

Power Measurement

In this section, the calculation of the power output of the RCG add-on cycle is illustrated. As the sensor attached to the generator is measuring the electrical current. Thus, the calculation of power is needed. Also, there are some limitations based on the voltage and the angular velocity of the shaft connected between the power turbine and the generator.

Working Principle

A schematic overview of the connections between the power turbine and the grid is given in Figure 39. The mechanical power of the power turbine (PT) is transferred to electrical power by the use of a generator (G). The power turbine and the generator are connected by use of a shaft. On this shaft, an angular velocity sensor (V) is connected which proves the angular velocity of both the generator and the power turbine. The voltage of the generator is controlled by use of the drive.

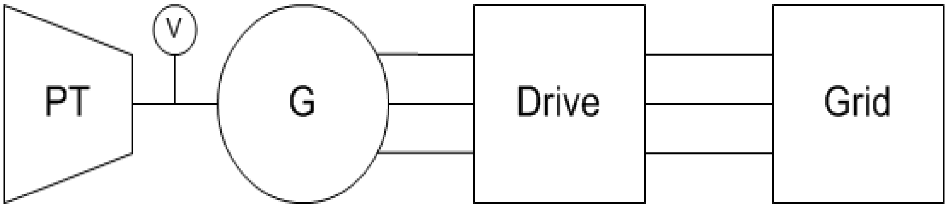


Figure 38 Schematic overview between power turbine and grid

The connection between the drive and the generator is excited as a triangle or star connection. This has a direct influence on the voltage and current of the line and phase. In the 5 kWe application, the generator is executed in a star connection.

Mathematical approach

Due to the star connection, the ratio between the line voltage U_L and phase voltage U_f and line current I_L and phase current I_f can be found in equation D.1 and equation D.2:

$$U_L = \sqrt{3} \cdot U_f \tag{D.1}$$

$$I_L = I_f \tag{D.2}$$

Given this, the power of the generator can be found in equation D.3:

$$P = \sqrt{3} \cdot U_L \cdot I_L \cdot \cos(\phi) = 3 \cdot U_f \cdot I_f \cdot \cos(\phi) \tag{D.3}$$

Where ϕ displays the angle between reactive and real power, which is a direct result of the ratio between the resistance and inductance of the coils. For every generator, this value is a fixed independent value. The line current I_L is measured in the drive. The drive provides the line voltage to the generator, which is based on the angular velocity of the shaft. The line voltage with respect to the angular velocity is displayed in Figure 40.

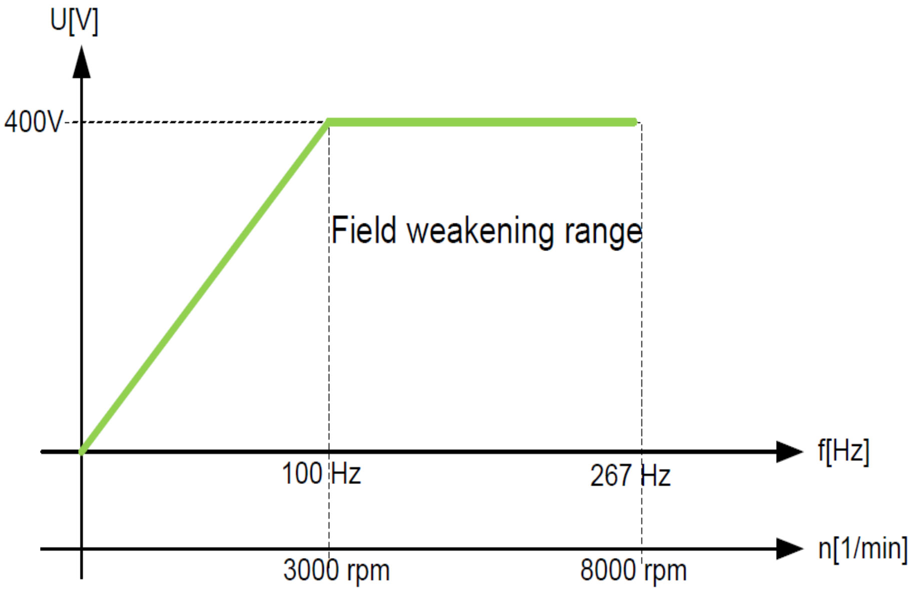


Figure 39 Line voltage with respect to angular velocity shaft

13 Appendix F: Construction of the heat exchanger

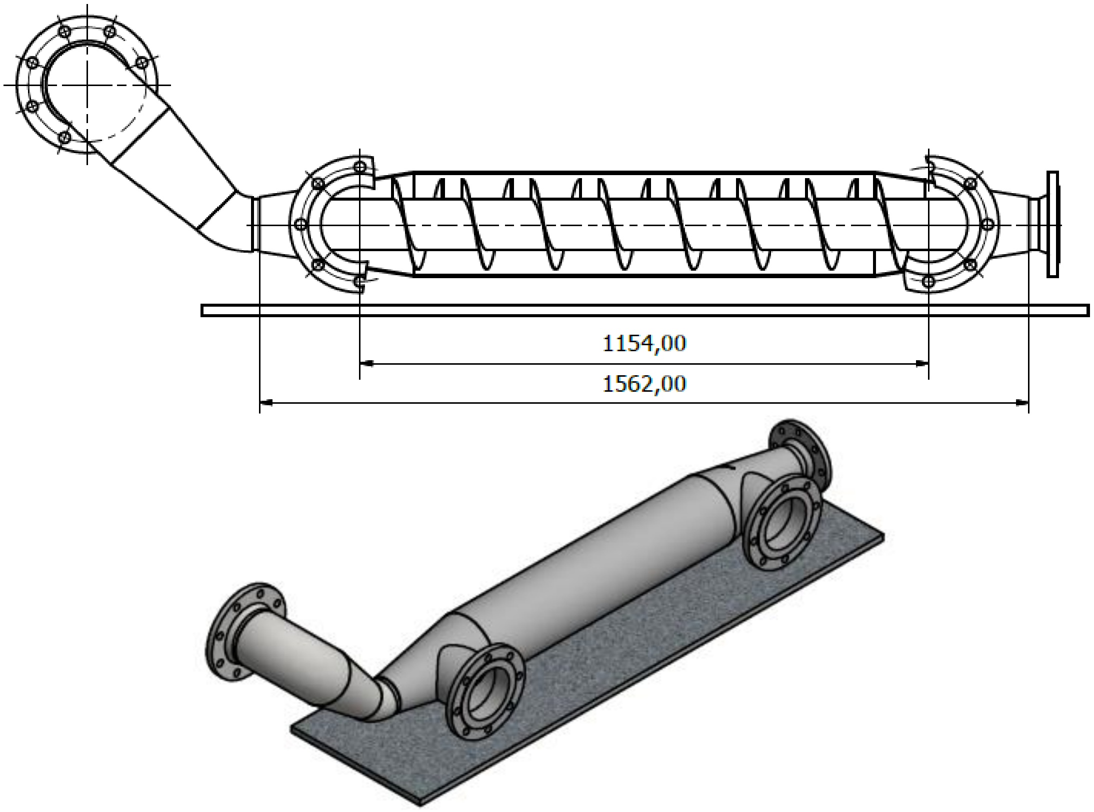


Figure 40 The design of the heat exchanger

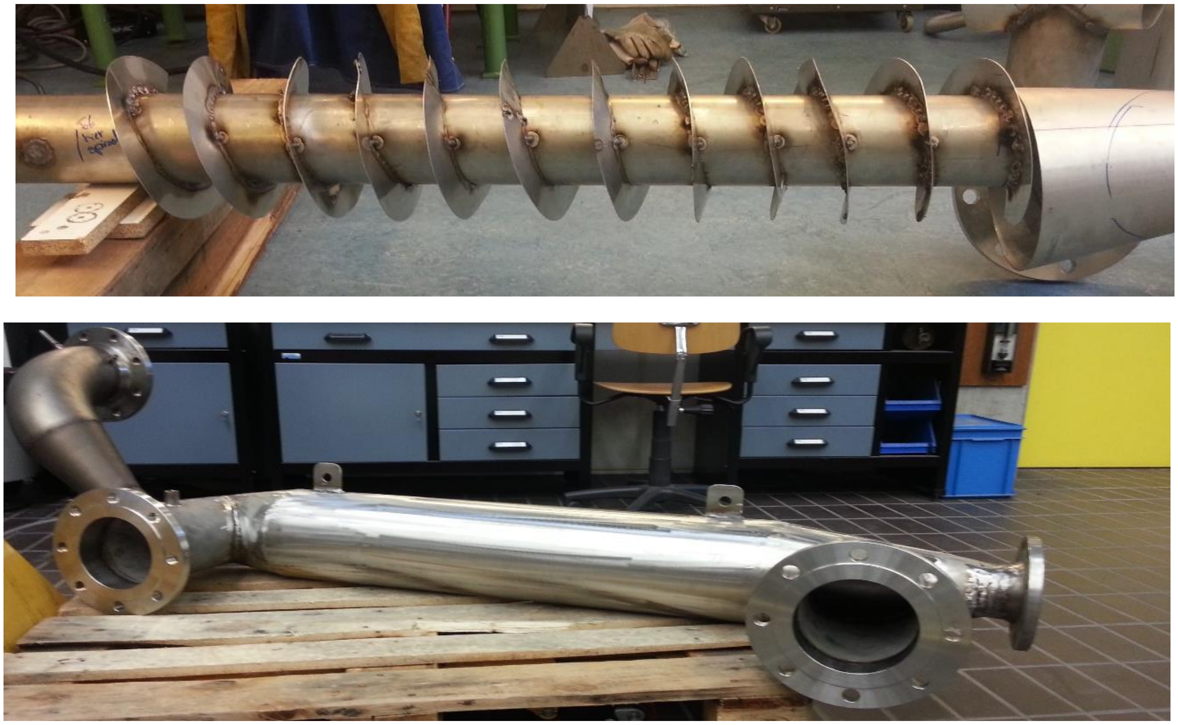


Figure 41 The constructed heat exchanger

According to the Autodesk Inventor, the heat exchanger has three different exchange surfaces:

- The surface inside the steam tube $A_{WW-st.in} = 0{,}514\ m^2$
- The surface outside the steam tube $A_{WW-st.out} = 0{,}536\ m^2$
- The surface of the fins $A_{WW-fins} = 0{,}418\ m^2$

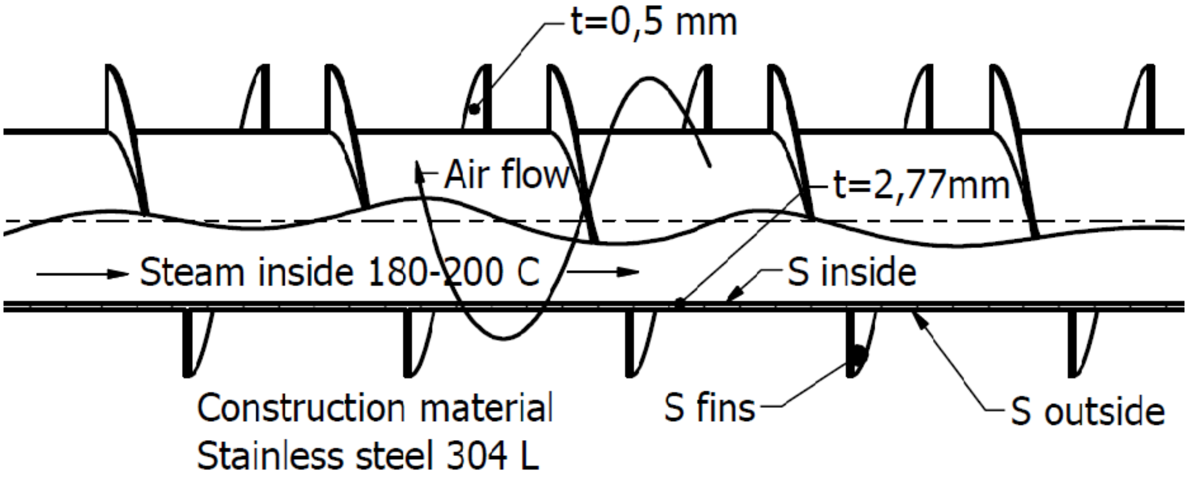


Figure 42 The heat transfer model of exchanger (steam to air)

The maximum allowable air through the heat exchanger:

Pmax	1,4 Bar
Pdis	1 Bar
Average air temperature	50°*C*
Minimum cross-section of the air path	0,01 m^2

$$V_{max} = \sqrt{2\frac{\kappa}{\kappa-1} rT(1 - \left(\frac{p_{dis}}{p_{max}}\right)^{\frac{\kappa-1}{\kappa}}} = 227\frac{m}{s} \tag{F.1}$$

$$m_{air\_max} = V_{max}A_{air\_} = 2{,}27kg/s \tag{F.2}$$

Heat transfer capacity expectation:

The efficiency of the fins:

$$L\sqrt{\frac{h}{kt}} = 1{,}8\sqrt{\frac{11{,}4}{42{,}9.5.\,10^{-4}}}$$
$$L = \frac{r_0}{r_{max}} = \frac{108}{180} = 1{,}8 \tag{F.3}$$

In which, the basic efficiency of the fins can be found from the following figure:

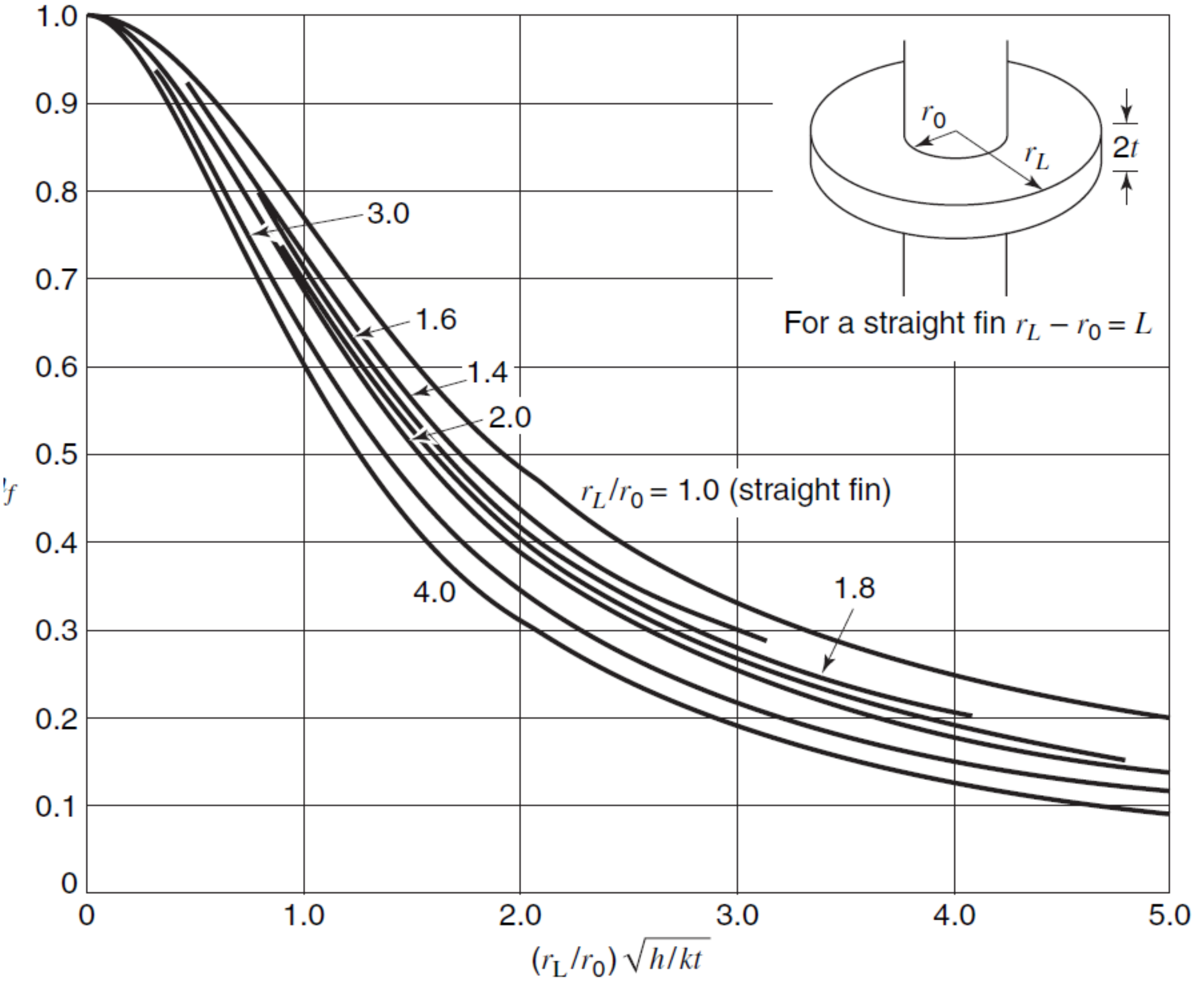


Figure 43 Different efficiency of Fins [27]

The efficiency μ_{fins} is chosen to be 0,1 and the heat transfer can be calculated as following:

$$q = h_{air}\Delta T_a(A_o + \mu_{fins}A_{fins}) \tag{F.4}$$

The calculated result of the heat transfer capacity is 1,45 kW. There is an assumption that steam heat coming from the turbine is 220 °C in addition to the air inlet temperature to be 20 °C. Moreover, the steam temperature doesn’t vary rapidly along the length of the exchanger.

Maximum working pressure

According to the stainless steel properties, maximum working pressure is considered. This can be calculated with the following equation:

$$P_{max} = 2\sigma_{314L}t_{tube}((d - 2t)SF) \qquad \text{(F.5)}$$

For the consideration of the maximum steam temperature, a temperature of 220 °C is considered. Additionally, a safety factory (SF=2) has been set. Thus, the maximum pressure inside the heat exchanger is 29 bars at the specified temperature. In the used application, a safety factor is 40 as the air pressure is 1,4 bar.

14 Appendix E: Fabrication of the RCG add-on at the TU/e lab

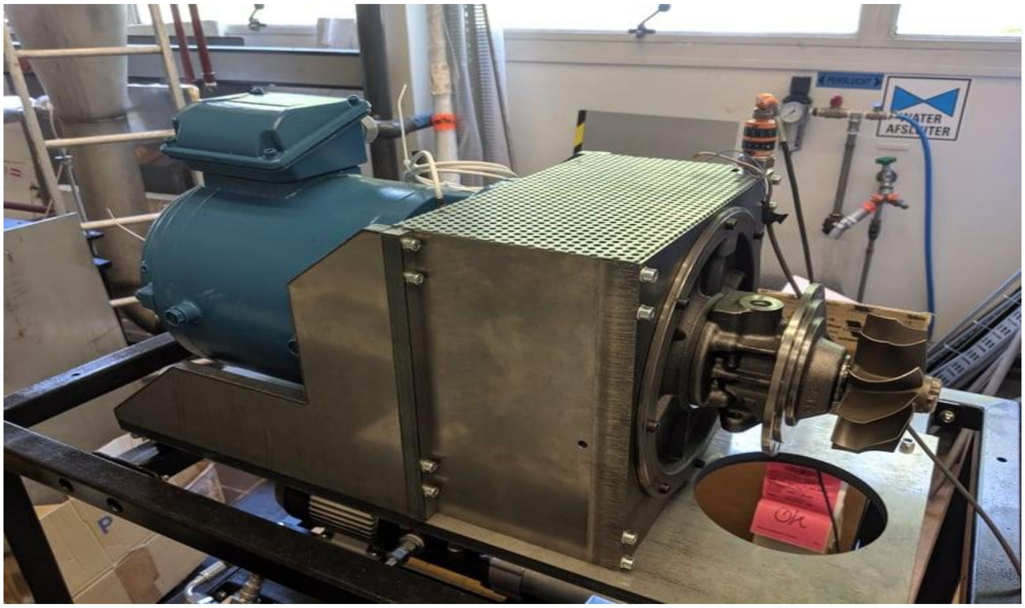


Figure 44 Gas Turbine

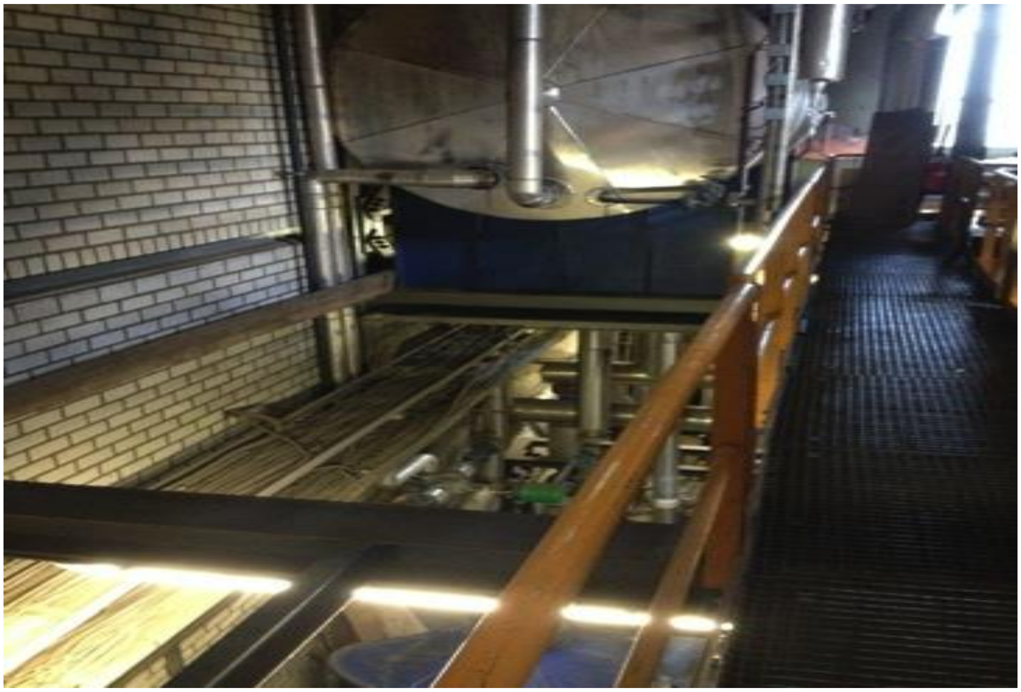


Figure 45 The decided location to install RCG add-on at HIS

Figure 46 The connection of RCG add-on to the main steam line