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TURBINE SEALING STEAM HEAT RECOVERY WITH DYNAMIC STIRLING ENGINES

IZRABA TOPLOTE TESNILNE PARE TURBINE Z DINAMIČNIMI STIRLING MOTORJI

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Keywords: analysis, Stirling engine, heat, working gas, sealing steam, steam turbine, regenerator, efficiency, isochoric compression

Abstract

This paper presents the possibilities of sealing steam heat recovery in a steam condensation turbine with the use of dynamic Stirling engines. The installation of dynamic Stirling engines into the turbine sealing steam system allows the recovery of sealing steam heat and the generation of electrical energy. The Stirling engine dynamics are expressed with a built-in working gas storage tank and working gas flow control to ensure adequate power output of the Stirling engine. The working gas quantity in the engine is controlled with regard to the available turbine sealing steam heat. Via the measurement of the turbine sealing steam quantity and quality, a model of the working gas pressure conditions in the Stirling engine is designed. The engine responsiveness at various working gas quantities and types is analysed.

Povzetek

V članku bomo predstavili možnosti izrabe toplote tesnilne pare parne kondenzacijske turbine z dinamičnim Stirling motorji. Z vgraditvijo dinamičnih Stirling motorjev v armaturo tesnilne pare tur-

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bine bomo izkoriščali toploto tesnilne pare in pridobivali električno energijo. Dinamika Stirling motorja se izraža z vgrajenim hranilnikom in regulacijo količine delovnega plina, ki poskrbi za ustrezno moč Stirling motorjev. Količina delovnega plina v motorju se uravnava glede na razpoložljivi toploto tesnilne pare turbine. S pomočjo opravljenih meritev količine in kvalitete tesnilne pare turbine, bomo izdelali model tlačnih razmer delovnega plina v Stirling motorju. Analizirali bomo odzivnost motorja pri različnih količinah in vrstah delovnih plinov.

1 INTRODUCTION

Sealing steam is steam-generated process during a steam turbine operation. Due to the leakage of high-pressure labyrinth seals, a constant sealing steam flow is created, used for the sealing of the low-pressure labyrinth seals, whereby the remaining flow is directed to the sealing steam condenser. The steam condenses in the sealing steam condenser and emits heat to the network water used for district heating. With the installation of Stirling engines into the sealing steam system, it is possible to produce thermal energy, as well as electrical energy. Stirling engines have been widely applied in various energy-related solutions, [1–5].

A Stirling engine is a heat engine using hot air and is considered to be one of the simplest engines and is the only one to use external combustion, in contrast to other engines. Its design is simple; it requires no fuel injection system and can use various types of fuels (biomass, coal, methane, hydrogen, etc.). The advantages of a Stirling engine in comparison with other heat engines are higher efficiency, lower environmental impact, no explosions taking place in a cylinder, and lower levels of noise and vibrations, [6]. One particular feature of Stirling engines is their heat regenerator, located in the engine cylinder air passage. The regenerator increases the engine efficiency by accumulating a portion of the heat of the working gas passing between the Stirling engine cylinders.

There are several types of engines, [7–10]. In practice, the alpha, beta, gamma and the combined configurations are most frequently used. The operating principle of all configurations is based on thermodynamic laws of working gas expansion and compression. In our case, a gamma configuration of the Stirling engine was chosen because the engine design allows the cylinders to be installed in separate locations.

The Stirling engine gamma configuration has two separate cylinders (a hot and a cold cylinder), [9]. The hot cylinder is mounted into the sealing steam system, whereas the cold cylinder is mounted outside the system and is additionally cooled. In our case, demineralised water (18°C) will be used for cooling to compensate for the losses during the process. A heat flow is created between the hot and the cold cylinders. The Stirling engine's power may be changed through a temperature difference of the hot and cold ends of the engine, through a compression ratio and the type and mass of the working gas. Furthermore, the selection of working gas impacts the engine's power, because working gases have different specific heat ratios.

Due to the structural properties of materials, the Stirling engine is designed for a particular gas, thus making any subsequent change in the engine working gas impossible. However, a change in the amount of the working gas during engine operation is possible. Such a change and a temperature change lead to a change in the pressure ratio in the engine, [11]. Everything indicated above must be taken into consideration in the engine design and construction.

2 MOUNTING AND CONTROL OF STIRLING ENGINES IN THE TURBINE SEALING STEAM SYSTEM

Due to the large amount of available heat of the turbine sealing steam, two Stirling engines operating in parallel and sharing a common generator will be installed into the sealing steam system. Each engine is built into its own system, allowing easier engine handling and operation. Two regulation circles will ensure the rational production of the Stirling engine's output. The first regulation circle will control the sealing steam quantity in the system in accordance with the energy needs. The second regulation circle will control the amount of the working gas in the Stirling engine in accordance with the available quantity of sealing steam. The mounting of the Stirling engine in the sealing steam system is illustrated in Figure 1.

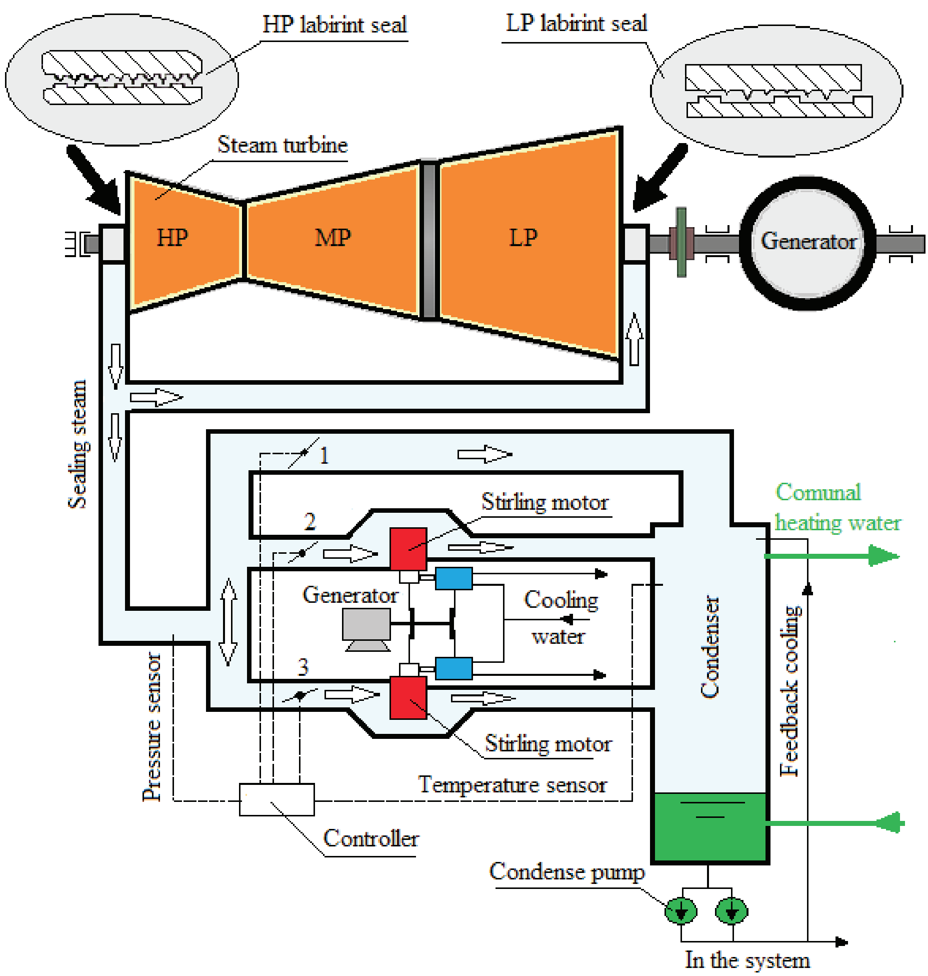

Figure 1: *Mounting of Stirling engines into the turbine sealing steam system*

The first regulation circle will control the position of Throttle 1, 2 and 3 in accordance with the energy needs (Figure 1). In normal operation, the position control of Throttles 2 and 3 maintains the required sealing steam pressure, varying with the change in the turbine load. Throttle 1 is in the closed position, and Throttles 2 and 3 control the amount of the sealing steam for the Stirling engine operation. If the demand for district heating increases, the controller will start opening Throttle 1 and closing Throttles 2 and 3 in accordance with the required sealing steam pressure and the network water temperature in the condenser. This will lead to an increase in the amount of the sealing steam towards the condenser and a decrease in the amount of sealing steam towards the Stirling engines.

In accordance with the amount of the sealing steam, the second regulation circle will change the working gas quantity and, therefore, the Stirling engine's power. A change in the amount of the Stirling engine's working gas will be carried out by placing an accumulation reservoir between the expansion and the compression space to control the amount of the working gas in the engine in accordance with the available sealing steam quantity. If less sealing steam is available, the working gas will be sent to the accumulation reservoir from the cylinder expansion area at a higher pressure. Moreover, conversely, with an increased amount of the sealing steam, the engine's power will be increased by feeding the working gas from the accumulation reservoir into the compression area of the engine. The control of engine working gas will be performed by means of two control valves, as illustrated in Figure 2. The accumulation reservoir has to be located on the hot cylinder in order to ensure that the accumulation reservoir pressure is always higher than the pressure in the compression cylinder.

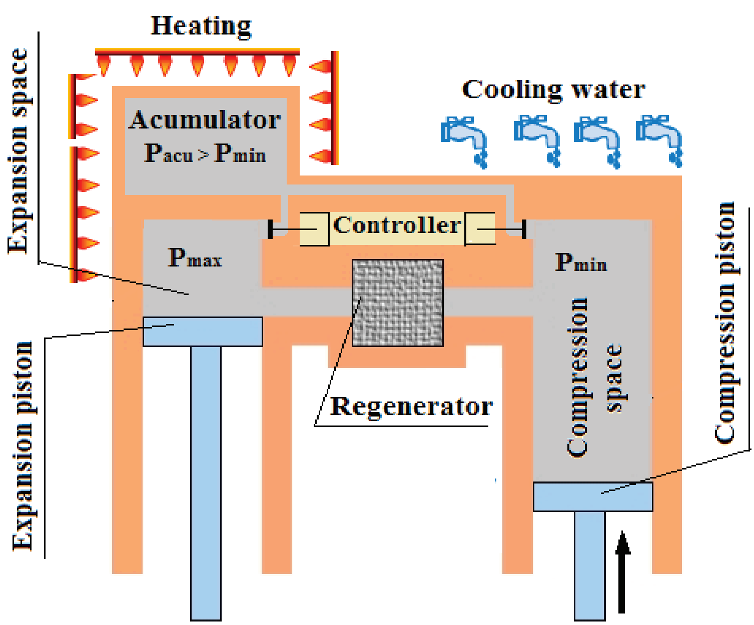

Figure 2: *Gamma-type Stirling engine with the working gas control*

The working gas serves as a substance to which heat is added or removed, resulting in the working gas expansion or compression with the internal mechanism being in motion. The choice of the working gas has a direct impact on the Stirling engine's efficiency, power, safety and general operation. Working gases have been widely applied in various energy related issues, [11-14]. The influencing factors in the working gas selection include price, flammability, viscosity, thermal conductivity, diffusivity, specific heat and electrical efficiency. Electrical efficiency is the ratio between the generated electrical energy and the Stirling engine input energy. It is expected that electrical efficiency varies according to the gas constant, i.e. the highest at air and the lowest at hydrogen, [11]. The thermodynamic properties of the working gases used in Stirling engines are indicated in Table 1.

Table 1: *Working gas properties*

Name	Symbol	Density	Gas constant
Helium	*He*	0.1785 kg/m³	2078 J/kgK
Air		1.2 kg/m³	259.8 J/kgK
Acetylene	C_2H_2	1.097 kg/m³	319.6 J/kgK
Ammonia	NH_3	0,73 kg/m³	488.3 J/kgK
Hydrogen	H_2	0,08987 kg/m³	4122 J/kgK
Freon	CF_2Cl_2	5.11 kg/m³	68.8 J/kgK

3 MATHEMATICAL ANALYSIS AND CALCULATION OF STIRLING ENGINE'S POWER OUTPUT

The Stirling engine can be used as a machine, a heat pump or a cooler, installed between a heat source (a heated body) and a heat sink (a cold body). The temperature difference between the bodies leads to a heat flow used by the heat engine. The regeneration that increases the efficiency of the engine will be taken into consideration in the calculation. Mathematical analysis has been widely applied in various energy related issues, [15–17].

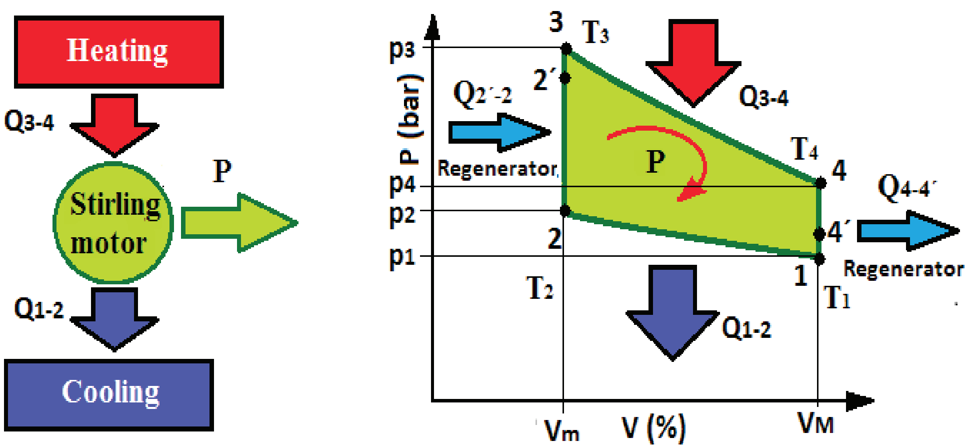

Figure 3: *Conversion of the working gas and generation of the Stirling engine work*

3.1 Stirling engine mathematical analysis

States 1 to 2 Isothermal compression (Figure 3).

The working fluid is in contact with the cold surface, where the working gas volume of the Stirling engine is reduced. The Boyle-Mariott law applies to the isothermal compression:

$$p \cdot V = m \cdot R \cdot T = cons\tan t \tag{3.1}$$

where p – working gas pressure (Pa),

V – working gas volume (m^3),

m – working gas mass (kg),

R – specific gas constant (J/kgK),

T – gas temperature (K).

The Stirling engine output heat (Q_{1-2}) is calculated using the following equation:

$$Q_{1-2} = p_1 \cdot V_1 \cdot \ln\frac{1}{\pi} = m \cdot R \cdot T_1 \cdot \ln\frac{1}{\pi} \tag{3.2}$$

where: Q_{1-2} – engine output heat (J),

p_1 – working gas pressure at point 1 (Pa),

T_1 – working gas temperature at point 1 (Pa),

V_1 – working gas volume at point 1 (m^3),

π - compression ratio of working gas conversion.

States 2 to 3 Isochoric compression (Figure 3).

The working gas is heated by means of the accumulated regenerator of the Stirling engine, where the temperature is isochorically increased from State T_1 to State T_4 (Figure 3). At this point, the working gas pressure is the highest. The accumulated regenerator input heat (Q_{1-2}) is calculated using the following equation:

$$Q_{2-3} = V_2 \cdot \left(\frac{p_3 - p_2}{\kappa - 1}\right) = m \cdot c_v \cdot (T_3 - T_2) \tag{3.3}$$

where: V_2 – working gas volume at point 2 (m^3),

p_2 – working gas pressure at point 2 (Pa),

p_3 – working gas pressure at point 3 (Pa),

κ - ratio of specific heats,

c_v – working gas specific heat at a constant volume (J/(kgK),

T_2 – working gas temperature at point 2 (K),

T_3 – working gas temperature at point 3 (K),

Regeneration entails a decrease in the input heat on account of the working gas regenerated heat.

The regeneration rate (σ) indicates how much heat has been regenerated in a particular circular process, and it is calculated using the following equation:

$$\sigma = \frac{T_{2'} - T_2}{T_3 - T_2} = \frac{T_3 - T_{4'}}{T_3 - T_2} \tag{3.4}$$

where: $T_{2'}$ - working gas temperature at point 2´ (K),

$T_{4'}$ - working gas temperature at point 4´ (K).

The thermal efficiency of the circular process, without a heat regenerator (η_t) is calculated:

$$\eta_t = \frac{(Q_{3-4} - Q_{1-2})}{(Q_{3-4} + Q_{2-3})} \tag{3.5}$$

where: $Q_{3\text{-}4}$ – input heat of the process 3-4 (J),

The thermal efficiency of the circular process with a heat regenerator ($\eta_{t,reg}$) is calculated:

$$\eta_{t,reg} = \frac{(Q_{3-4} - Q_{1-2})}{Q_{3-4}} = 1 - \frac{T_2}{T_3} \tag{3.6}$$

States 3 to 4 (Figure 3) Isothermal expansion.

The working gas is in contact with the heated surface, where the volume of the Stirling engine working gas is increased. The expansion piston performs the work, the volume increases, and the pressure drops at the working gas maximum temperature (T_4). The Boyle-Mariott law applies to isothermal expansion (Equation 3.1).

The input heat of the process ($Q_{3\text{-}4}$) is calculated:

$$Q_{3-4} = p_3 \cdot V_3 \cdot \ln \pi = m \cdot R \cdot T_4 \cdot \ln \pi \tag{3.7}$$

where: V_3 – working gas volume at point 4 (m^3).

The pressure at working point 4 (p_4) is calculated:

$$p_4 = \frac{p_3 \cdot V_3}{V_4} = \frac{p_3}{\pi} \tag{3.8}$$

where: V_4 – working gas volume at point 4 (m^3)

State 4-1 (Figure 3) Isochoric expansion.

The working gas emits the heat to the regenerator that accumulates it, and it is cooled down from state T_4 to state T_4´ (Figure 3). The regenerator output heat ($Q_{4\text{-}4'}$) equals the regenerator input heat ($Q_{2\text{-}2'}$), multiplied by the regeneration loss (η_e), and is calculated:

$$Q_{4-4'} = V_4 \cdot \frac{(p_{4'} - p_4)}{(\kappa - 1)} = m \cdot c_v \cdot (T_{4'} - T_4) = Q_{2'-2} \cdot \eta_e \tag{3.9}$$

where: $p_{4'}$ - working gas pressure at point 4´ (Pa),

p_4 – working gas pressure at point 4 (Pa).

Calculation of power

The Stirling engine's power (P) is the difference between the engine input and output heat multiplied by a loss factor (η_{em}). The Stirling engine's power output is calculated:

$$P = (Q_{3-4} - Q_{1-2}) \cdot \eta_{em} \tag{3.10}$$

The Stirling engine's efficiency (η) is the ratio between the work done and the input heat flow and is calculated using the following equation:

$$\eta = \frac{m \cdot R \cdot \ln \pi \cdot (T_4 - T_1) \cdot V}{m \cdot V \cdot c_v (T_4 - T_1) + R \cdot T_4 \cdot \ln \pi} = \frac{\ln \eta (T_4 - T_1) \cdot (\kappa - 1)}{(T_4 - T_1) + T_4 \cdot \ln \pi \cdot (\kappa - 1)} \tag{3.11}$$

3.2 Stirling engine power calculation

In order to calculate the Stirling engine's power, the quality and quantity of the sealing steam of a condensation turbine at a Slovenian district heating plant were analysed. The sealing steam pressure oscillation was established ranging between 1.7 bar to 2.4 bar or 2.1 bar on average in a two-month period. The pressures are absolute. The sealing steam temperature varies between 260 °C and 300 °C and amounts to 280 °C on average in a two-month period. The sealing steam quantity varies between 1.2 kg/s and 2 kg/s. After the establishment of the quality of the sealing steam, heat can be determined by means of the enthalpy differential to be used for the operation of the Stirling engines. The enthalpy differential (Points 1 and 2) is illustrated in Figure 4.

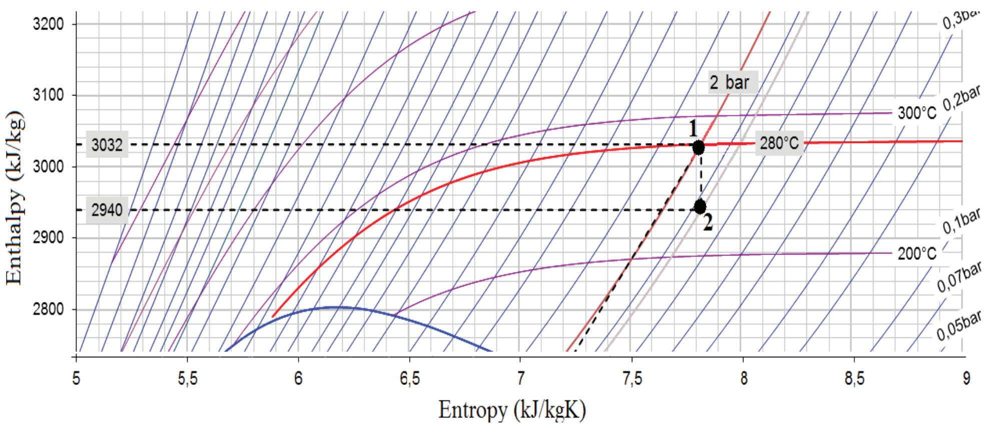

Figure 4: *Sealing steam enthalpy differential used for the operation of the Stirling engines*

If a drop in enthalpy of 92 kJ/kg is multiplied by the quantity of the sealing steam (1.6 kg/s), the power output to be used by the Stirling engine is obtained, and it amounts to 147 kW. If the sealing steam heat is used when a portion of the steam is directly led to a condenser via System 1 (Figure 1) 0.8 kg/s of the sealing steam or 74 kW of power may be used. A Stirling engine capable of using the sealing steam heat from 70 kW to 140 kW has to be designed. Considering that two Stirling engines operating in parallel will be mounted into the sealing steam system, the engine dimensions have to be such as to ensure the use of the sealing steam heat from 35 kW to 70 kW. Helium has been chosen as the Stirling engine working gas. The thermodynamic states of the working gas (helium) at points indicated in Figure 3 were calculated using the equations indicated in Chapter 3.1. The results are illustrated in Table 2.

Table 2: *Thermodynamic states of helium by point when using 35 kW and 70 kW*

Name	*Symbol*	At 35 kW	At 70 kW
Minimum temperature	T_1	291 K	291 K
Maximum temperature	T_4	535 K	567 K
Expanded gas pressure	p_1	$3.7093x10^5$Pa	$7x10^5$ Pa
Gas pressure, *Pa*	p_2	$14.837x10^5$ Pa	$28x10^5$ Pa
Compressed gas pressure	p_3	$27.278x10^5$Pa	$54.557x10^5$ Pa
Gas pressure	p_4	$6.8196x10^5$ Pa	$13.639x10^5$ Pa
Expanded gas volume	V_1	0.037022 m^3	0.037022 m^3
Compressed gas volume	V_2	0.009255 m^3	0.009255 m^3
Compression rate	π	4	4
Helium specific heat ratio	κ	1.66	1,66
Mass of the gas in the system	*m*	0.02271 kg	0.042856 kg

Once the thermodynamic states of the working gas (helium) are known, the heat levels of the process, the engine's power output and the Stirling engine's thermal efficiency can be calculated. The results are indicated in Table 3.

Table 3: *Heat, power output and efficiency at 35 kW and 70 kW*

Name	Symbol	At 35 kW	At 70 kW
Process input heat	Q_{3-4}	35 kW	70 kW
Process output heat	Q_{1-2}	19.037 kW	35.926 kW
Regeneration heat	Q_{2-3}	17.446 kW	37.241 kW
Engine power output	*P*	15.483 kW	33.051 kW
Thermal efficiency with regeneration	$\eta_{t,reg}$	0.44	0.47

The results show that if using 70 kW of the sealing steam heat, the Stirling engine generates 33.051 kW of power and reaches 47% efficiency. If the Stirling engine uses 35 kW of the sealing steam heat, it generates 15.483 kW of power and reaches 44% efficiency. As two Stirling engines are mounted in the sealing steam system, the total maximum power is 66.102 kW and the minimum power 30.966 kW.

4 STIRLING ENGINE MODELLING

The Stirling engine responsiveness to a change in the sealing steam quantity will be established through modelling. The model is designed using the Matlab-Simulink software tool and comprises the main programme and subprograms (the main program interconnects the subprograms). The subprograms compute the sought values at a specific order. Figure 5 illustrates the Stirling model.

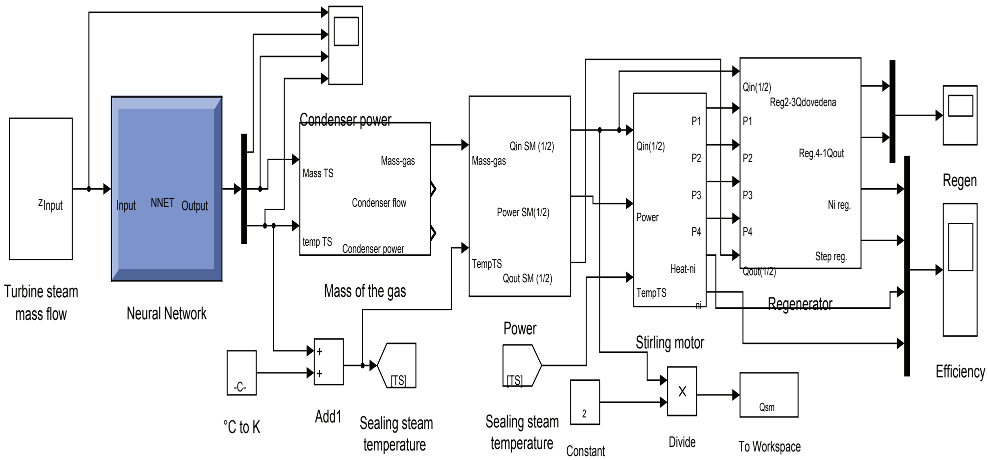

Figure 5: *Stirling engine model, [18]*

The neural network subprogram is a pre-trained network. The input data was given in a matrix format [1×2366]. The output data in a matrix format [3×2366] describe the sealing steam temperature, quantity and pressure. A neural network was designed on the basis of the input data of one group (amount of steam admitted to the turbine) and the results in three groups (sealing steam temperature, quantity and pressure). The neural network contains two groups of 90×10 hidden neurons. Other authors has been widely applied the neural network in various energy related issues, [19-22]. The neural network architecture is shown in Figure 6.

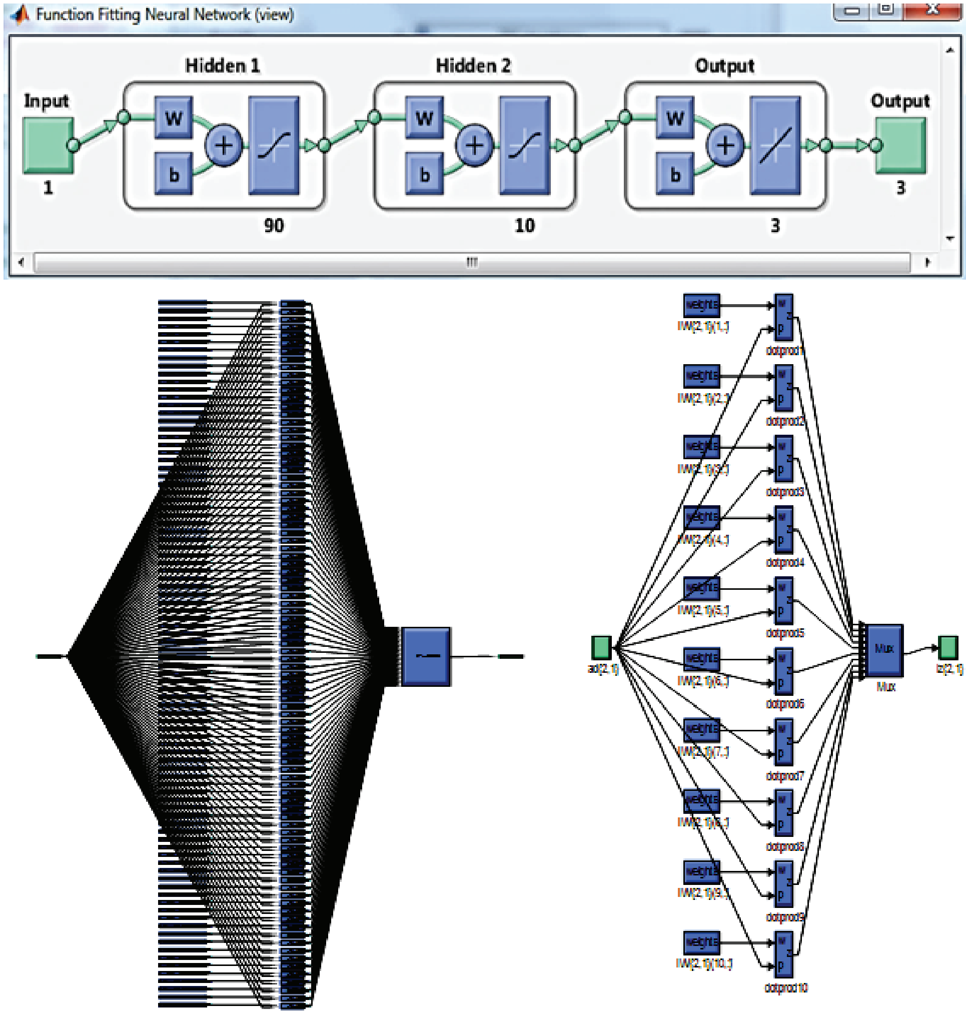

Figure 6: *Neural network architecture, [18]*

Figure 7 shows the results of the input–output data fit of the trained neural network, including any errors.

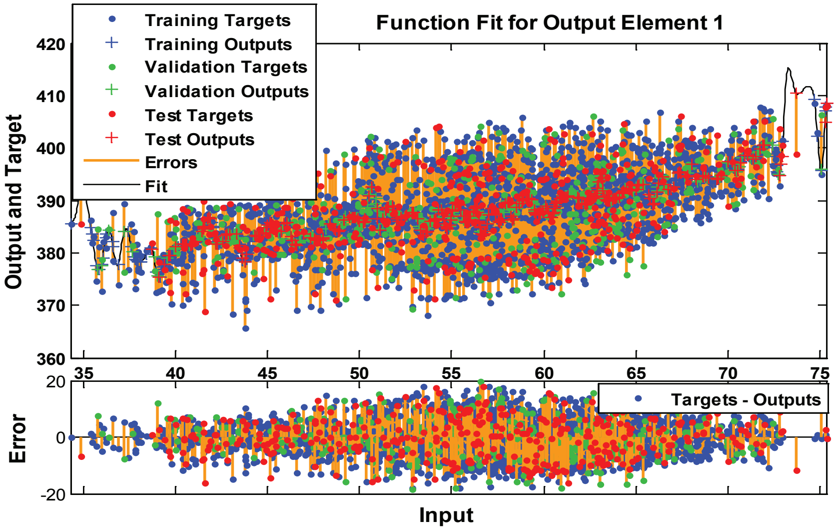

Figure 7: *Neural network matching with input-output data, [18]*

When the quantity of the sealing steam is known, it is possible to compute thermal power of the sealing steam to be used for the Stirling engine operation and the district heating (condenser). Moreover, the amount of the working gas in the Stirling engine is computed. The data on the working gas quantity is the input data of the third model subprogram (Power output, Figure 5). The above subprogram computes the input and output heat for the Stirling engine operation with the difference representing the engine's power output. If the power output is multiplied by the engine efficiency rate, the actual power output of the engine is obtained. The actual engine power output constitutes the input data of the fourth subprogram (Stirling engine, Figure 5) that computes the working gas efficiency and thermodynamic properties. The model's fifth subprogram (Regeneration, Figure 5) computes the Stirling engine's regeneration rate and efficiency.

4.1 Results of the Stirling engine

In the Stirling engine model analysis, the engine working gas quantity varied according to the sealing steam quantity. At the sealing steam amount of 0.8 kg/s, the engine operates at a minimum working gas quantity. By increasing the sealing steam quantity, the quantity of the working gas in the engine starts to increase. The engine operates at a maximum working gas quantity if the sealing steam flow exceeds 1.6 kg/s. Equation 4.1 describes the pace of change in the working gas quantity with regard to the change in the sealing steam quantity. Figure 8 shows the results of the equation.

$$\begin{aligned} m = f(m_{ss}) = {} & 0,05254 + 0,005581 \cdot \cos(m_s \cdot 1,496) - 0,033 \cdot \sin(m_s \cdot 1,496) - \\ & 0,01203 \cdot \cos(2 \cdot m_s \cdot 1,496) - 0,02112 \cdot \sin(2 \cdot m_s \cdot 1,498) - \\ & 0,0103 \cdot \cos(3 \cdot m_s \cdot 1,496) + 0,00169 \cdot \sin(3 \cdot m_s \cdot 1,496) - \\ & 0,002356 \cdot \cos(4 \cdot m_s \cdot 1,496) + 0,003772 \cdot \sin(4 \cdot m_s \cdot 1,496) \end{aligned} \quad (4.1)$$

where: m_{ss} – sealing steam quantity.

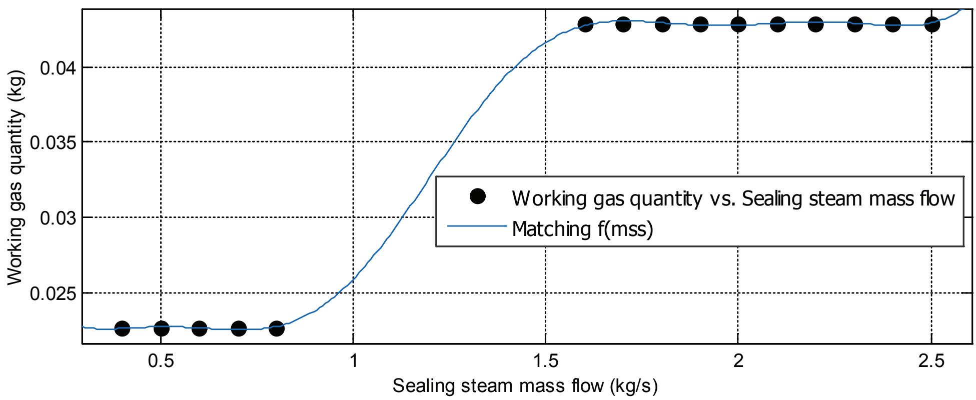

Figure 8: *Stirling engine working gas quantity vs. sealing steam mass flow, [18]*

The model input data includes sinusoidal oscillations of the Stirling engine working gas quantity and temperature, i.e. between the minimum (0.02271 kg/s and 535 K) and maximum value (0.042856 kg/s and 567 K) as shown in Figure 9. The results of the Stirling engine model are plotted for one engine.

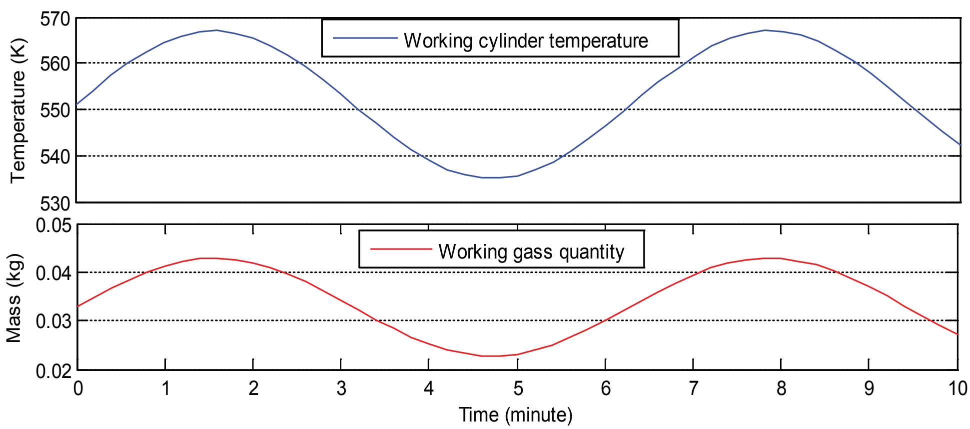

Figure 9: *Input data of the Stirling engine model, [18]*

The results of the input and output heat change model show that between 35 kW and 70 kW of the sealing steam heat (input heat) is used for the Stirling engine's operation. With the cooling of the Stirling engine's compression cylinder, the output heat ranges from 20 kW to 35 kW. The engine's power output is the difference between the input and output heat multiplied by the factor of losses and varies from 13 kW to 32 kW. The results of the Stirling engine's power output model are shown in Figure 10. The blue area represents the heat needed by the Stirling engine to operate, whereas the red area represents the heat output due to the Stirling engine cooling. The difference is the engine's power output. As is evident from Figure 10, the engine's power output increases nonlinearly as the input heat increases, on the basis of which the range of the engine's rational operation may be established.

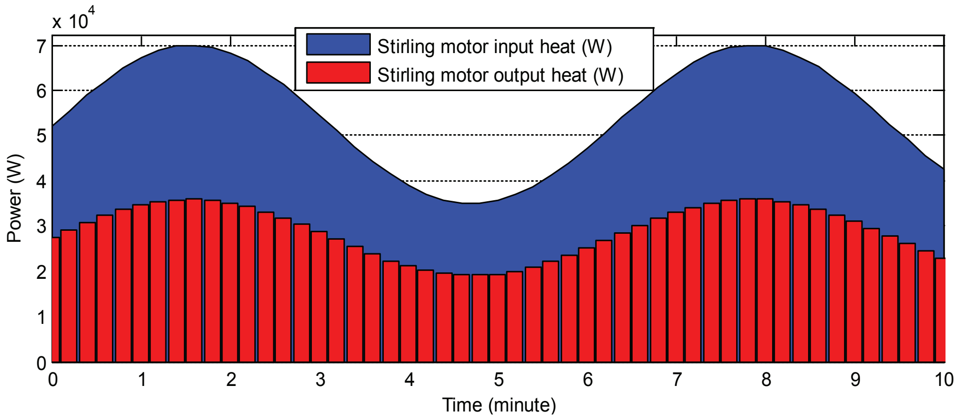

Figure 10: *Stirling engine input heat, output heat and power, [18]*

The results of the regeneration heat model show that regeneration leads to certain losses. The regenerator heat loss is represented by the green area in Figure 11. The blue area represents the regenerator input heat and the red area the regenerator output heat.

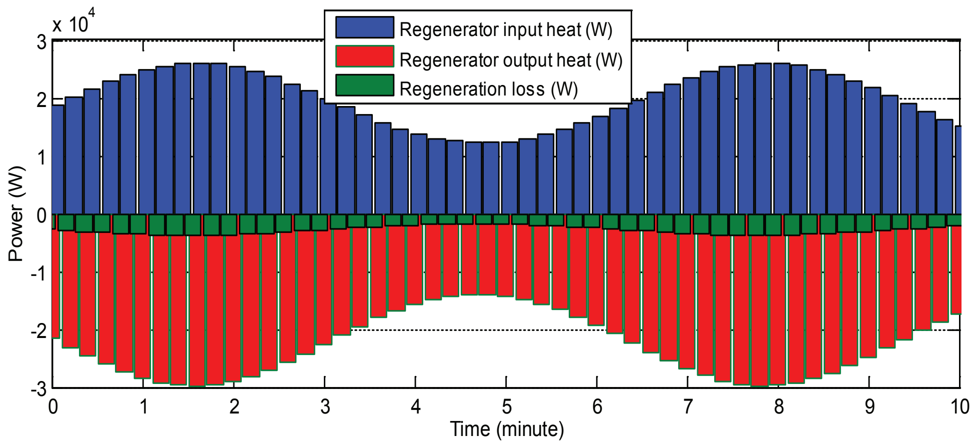

Figure 11: *Stirling engine regeneration heat, [18]*

The results concerning the efficiency reveal an optimum point of the Stirling engine operation, i.e. at a maximum load when the efficiency is the highest. The Stirling engine maximum efficiency using regenerative heat amounts to 46.4% and as low as 33.5% without using regenerative heat. The Stirling engine minimum efficiency is at the minimum engine load. The minimum efficiency using regenerative heat is 45.4% and only 32.8% without using regenerative heat. The Stirling engine's efficiency increases by 12% as a result of the use of the working gas regenerative heat. Figure 12 shows the Stirling engine's efficiency.

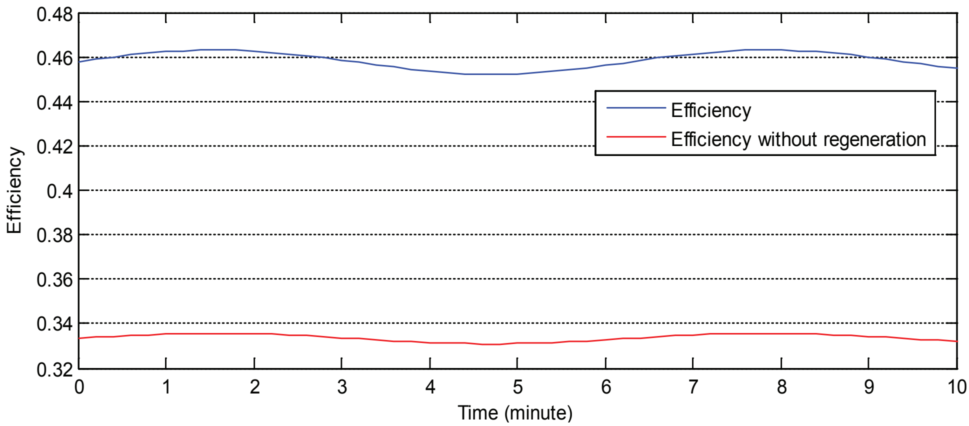

Figure 12: *Stirling engine efficiency, [3]*

The heat flows, working gas pressure and volume variations at the Stirling engine sinusoidal power oscillation are shown in Figure 13.

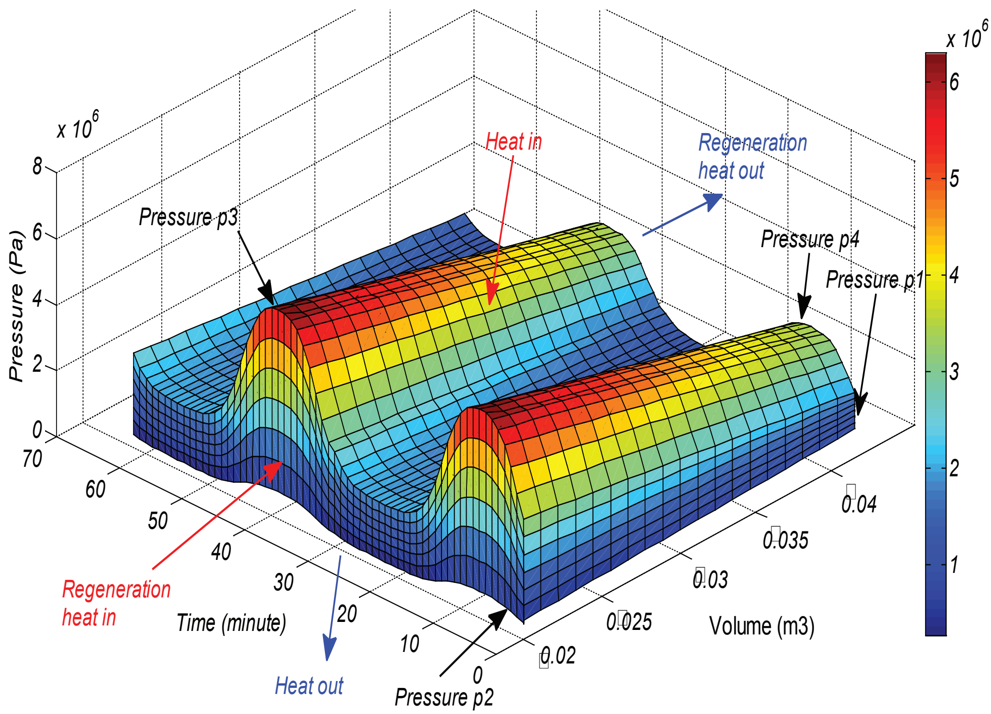

Figure 13: *Dynamic p – V diagram, [18]*

Furthermore, simulations of the Stirling engine operating with various working gases were carried out on the existing model. The simulations were carried out by using the gas constants in the model as indicated in Table 1. Figure 14 shows the variation of pressure p_3, i.e. the maximum Stirling engine pressure.

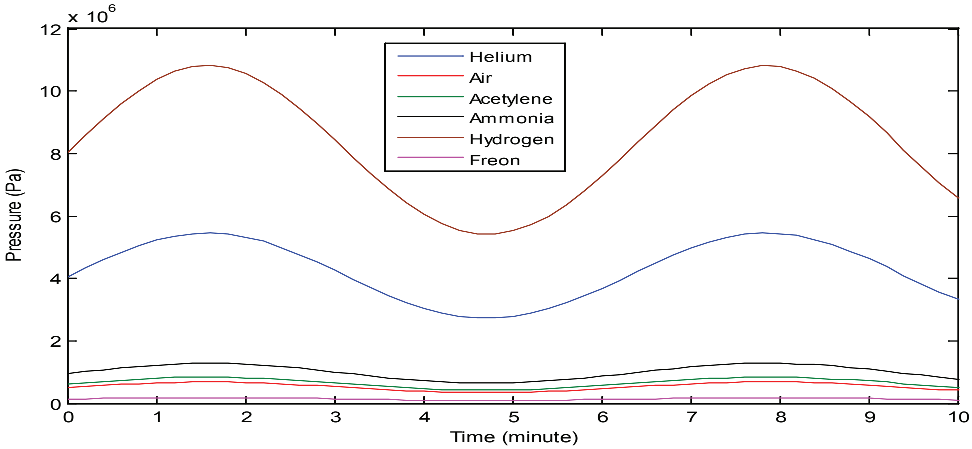

Figure 14: *Variation of pressure p_3 at various Stirling engine working gases, [18]*

Figure 14 shows that the highest pressure is achieved with hydrogen and the lowest with Freon. The choice of the engine working gas has to be anticipated prior to designing an engine, as the specification of the engine materials should be suitable for the thermal and pressure state. As the working gas pressure state is closely related to the engine's power, the variation in power at different working gases is equivalent to the pressure state. Figure 15 illustrates the Stirling engine's power output variations at different working gases.

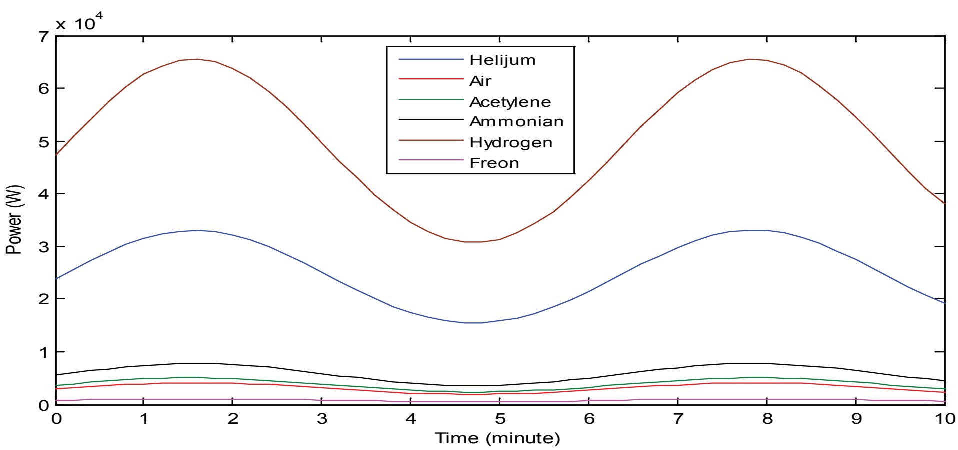

Figure 15: *Stirling engine power output variations at different working gases, [18]*

5 CONCLUSION

This paper presents the possibility of using the sealing steam heat of a turbine for heating and power generation. The possibility of using the sealing steam heat that varies in accordance with the energy needs has been indicated. The use of the sealing steam heat for Stirling engines results in electrical energy generation and the application of the engine output heat for the heating of the demineralised supplementary water of a boiler. In the event of an increase in demand for district heating, the sealing steam control system reduces the Stirling engine's power output and increases the heating power. The Stirling engine adapts to the above changes by varying the working gas quantity and adjusting the power to the energy needs.

The installation of Stirling engines into thermal plants is suitable for the use of a smaller amount of waste heat as the issue of overly large engine capacity emerges with larger amounts of waste heat. The above issue is addressed by mounting Stirling engines of a smaller capacity in a successive or a serial-parallel arrangement.

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Nomenclature

c_v Specific heat
m Mass
p Pressure
P Power
R gas constant
T temperature
V Volume
Q Heat
σ Regeneration rate
κ ratio of specific heats
η efficiency
π compression ratio