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Energy Conversion and Management 47 (2006) 894–908

ENERGY CONVERSION & MANAGEMENT

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Numerical study on optimal Stirling engine regenerator matrix designs taking into account the effects of matrix temperature oscillations

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Received 12 December 2004; accepted 10 June 2005
Available online 1 August 2005

Abstract

A new regenerator matrix design that improves the efficiency of a Stirling engine has been developed in a numerical study of the existing SM5 Stirling engine. A new, detailed, one-dimensional Stirling engine model that delivers results in good agreement with experimental data was used for mapping the performance of the engine, for mapping the effects of regenerator matrix temperature oscillations, and for optimising the regenerator design. The regenerator matrix temperatures were found to oscillate in two modes. The first mode was oscillation of a nearly linear axial matrix temperature profile while the second mode bended the ends of the axial matrix temperature profile when gas flowed into the regenerator with a temperature significantly different from the matrix temperature. The first mode of oscillation improved the efficiency of the engine but the second mode reduced both the work output and efficiency of the engine. A new regenerator with three differently designed matrix sections that amplified the first mode of oscillation and reduced the second improved the efficiency of the engine from the current 32.9 to 33.2% with a 3% decrease in power output. An efficiency of 33.0% was achievable with uniform regenerator matrix properties.

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doi:10.1016/j.enconman.2005.06.006

Keywords: Stirling engine; Regenerator; Matrix temperature oscillations; Simulation

1. Introduction

The Stirling engine is a closed cycle, regenerative, external combustion engine. In a Stirling engine, work is expended to compress a cold gas, and the gas is then heated to further increase the pressure. The hot, high pressure gas is then expanded, and more work can be extracted than was needed to compress the cold gas. Finally, the gas is cooled before the next cycle begins with a new compression. The heating and cooling of the working gas is achieved by sending the working gas back and forth through a serial connection of heat exchangers, i.e. a cooler, a regenerator and a heater. The regenerator is a void filled with a porous matrix with a large heat transfer area and a large heat capacity, made, for instance, from metal felt. The main purpose of the regenerator is to act as a thermal heat storage that minimises the amount of energy that must be added in the heater, thereby increasing the thermal efficiency. The regenerator does this by absorbing energy when the gas is flowing from the heater towards the cooler and releasing the energy again when the gas is flowing from the cooler towards the heater. Because the matrix alternately absorbs and releases energy, the temperature profile of the matrix oscillates in time.

Because of their large heat transfer area, porous matrix regenerators also, typically, greatly increase the heat transfer in an engine and, hence, increase the power output. Regenerators and their design are, thus, central to the performance of Stirling machines, and their influence on the performance of the machines has been studied intensively. Both efficiency and a high power output are important because they influence the cost of power produced by an engine. Furthermore, the efficiency directly influences the environmental impact per unit produced power. This paper presents a new way to design regenerator matrices so that Stirling engines can achieve higher efficiencies while maintaining a high power output. The new design is based on the results of a numerical study on the influence of the regenerator matrix temperature oscillations on the performance of a Stirling engine.

1.1. Previous regenerator studies

Experimental studies of regenerators have mostly been conducted in order to generate correlations for heat transfer and flow friction, such as those compared by Thomas and Pittman [1], that can be used in simulation programs. Several experimental studies, for instance, the work of Gedeon and Wood [2] and of Isshiki et al. [3], have been performed by placing small samples of regenerator matrix material into specialised regenerator test equipment instead of performing the measurements on complete regenerators inside actual engines. These studies have yielded information about the flow friction and heat transfer in regenerator matrices, but they do not show the influence of regenerator performance on machine performance. In the heat transfer study by Siegel [4], measurements have been performed on a full regenerator inside an actual Stirling engine, but it has only been possible to measure bulk temperatures and pressure losses that result from the combined effects of all phenomena, such as heat transfer, matrix temperature oscillations and flow friction, occurring in the regenerator in the engine; the influence of the individual phenomena has not been revealed.

Analytical and semi-analytical studies of Stirling machines require that the equations and boundary conditions of the models be simple enough that analytical solution methods can be successful applied. Hence, significant simplifications compared to real world conditions are needed, and the agreement between predicted and actual machine performance suffers accordingly. Analytical models, however, are useful for identifying phenomena and for predicting trends. In 1982 and 1986, Jones used an analytical model with a piece wise linear axial matrix temperature profile to show that matrix temperature oscillations influence the performance of Stirling engines because they induce a heat pumping effect and cause a loss of power output [5,6]. More recently, Bauwens has shown that thermoacoustic effects in regenerators can be significant when the flow passages in the regenerator are of significant magnitude compared to the heat penetration depth in the gas [7].

Detailed numerical studies of regenerators, see, for instance, the work of Gary et al. from 1984 [8], have been performed. When the regenerator models are not integrated into detailed and complete machine models, the influence of the regenerators on their own boundary conditions and on machine performance cannot be determined.

1.2. Regenerator matrix design

The design of metal felt regenerators can be characterised by the geometry of the regenerator volume, the diameter of the wire from which the metal felt is made and the fill factor (or, conversely, the void fraction) of the metal felt. In this study, only the wire diameter and fill factor are considered.

The amount of heat that must be added in the heater of a Stirling engine can be reduced by decreasing the net average flux of energy that is carried from the heater to the cooler by the gas in the engine, i.e. by reducing the regenerator loss. The regenerator loss can be reduced by reducing the temperature difference between the gas and the matrix by increasing the heat transfer area per unit volume. The heat transfer area can be increased by reducing the wire diameter and/or by increasing the fill factor but doing so will increase the flow resistance. Pressure losses caused by flow resistance in the regenerator cause a loss of power output from the engine.

When a regenerator design is optimised without taking into account the effects of matrix temperature oscillations on engine performance, a design that balances the heat transfer properties and the flow resistance in the matrix can be found. In this study, matrix temperature oscillations are taken into account and regenerator designs that take into account the thermal inertia of the matrix in addition to the heat transfer properties and flow resistance are discussed.

1.3. The effects of matrix temperature oscillations

The findings of Jones [6] suggest that the magnitudes of the heat pumping and power loss induced by regenerator matrix temperature oscillations are inversely proportional to the heat capacity of the matrix and, hence, to the magnitudes of the matrix temperature oscillations. The study of Jones does not account for the influence of the matrix temperature oscillations on the boundary conditions of the regenerator. We have presented results [9] that indicate that the inverse proportionalities are only approximate. Still, this dependence on the heat capacity of the matrix makes it possible to extrapolate reliably to the case of infinite matrix heat capacity from simulations performed with finite matrix heat capacity. If, for instance, simulations are performed where the heat capacity of the matrix is increased by a factor of 100, the magnitudes of the effects of matrix temperature oscillations are reduced to the fraction 0.01; the extrapolation from this case to the case of infinite matrix heat capacity is a small one.

1.4. The present study

The effects of regenerator matrix temperature oscillations on the performance of a Stirling engine have been studied by using a detailed Stirling engine model to map the performance of an existing Stirling engine and the effects of matrix temperature oscillations for a wide range of regenerator matrix designs. The information gained about the influence of different modes of matrix temperature oscillations on the performance of the engine leads to a suggestion for a new regenerator matrix design where the regenerator is divided into three sections with different matrix designs. The new regenerator design allows the engine to obtain a higher efficiency than can be achieved with a regenerator with a uniform matrix design while maintaining a high power output.

2. Methods

2.1. The studied Stirling engine

The engine design parameters and operating conditions used as input for the Stirling engine model in this study were based on the 9 kW β-type Stirling engine, SM5 [10]. The engine is a hermetically sealed unit and has a generator built into a sealed and pressurized crank case. The regenerator of the engine is an annular shaped void with a stainless steel felt matrix. A picture of the engine and a drawing of the cylinder region of the engine are shown in Fig. 1.

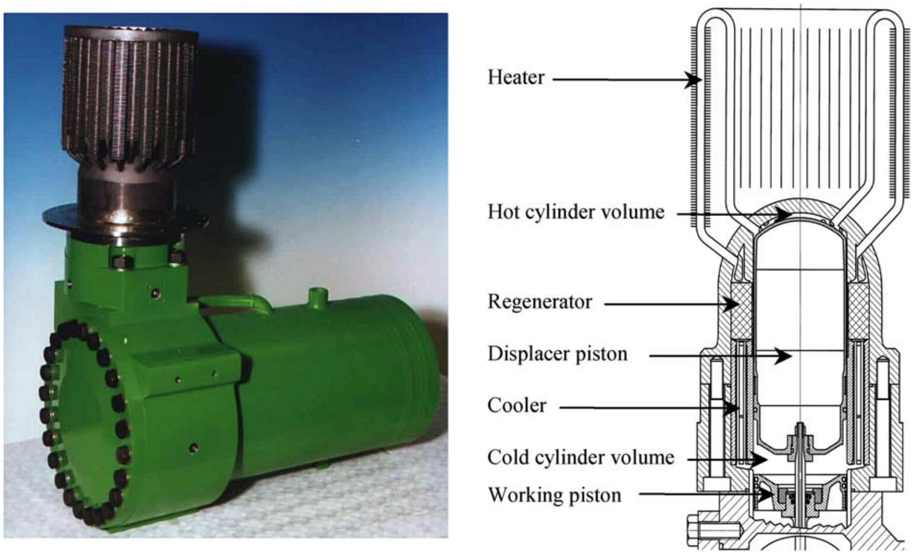


Fig. 1. The SM5 Stirling engine with exposed heater (left) and a drawing of the cylinder region of the engine.

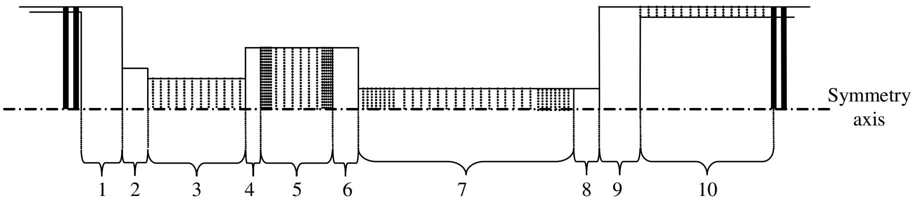
2.2. The Stirling engine model

In this study, we used a new Stirling engine model that we have documented [9] is capable of delivering results that are in good agreement with experimental data over a wide range of operating conditions with both helium and nitrogen as working gas. This Stirling engine model is a refinement of the modelling approach we first presented in Ref. [11]. We have documented [9,11] that the model is able to reproduce the heat pumping and power loss effects caused by the matrix temperature oscillations that were originally predicted by Jones [5,6].

The outer boundary conditions of the model are the temperature profile on the outside of the heater tubes, the power outlet from the generator and the flow rate and temperature of the cooling water. Because the model does not include the burner system, the heat intake and electrical efficiency calculated by the model is based on the heat absorbed by the heater tubes and do not include burner losses.

In the model, an equivalent one-dimensional geometry is used to represent the working volume of the Stirling engine, i.e. the computational domain. The computational domain includes the displacer piston clearance gap and the manifolds of the engine in addition to the cylinder volumes, cooler, regenerator and heater. In the displacer piston clearance gap, the control volumes follow the motion of the displacer piston, but everywhere else in the engine, the control volumes are fixed in space. The discretization of the computational domain into control volumes was locally refined where solutions contain large gradients, and this was done so that grid convergent solutions were obtained throughout the studied range of regenerator designs. The discretization of the computational domain is illustrated in Fig. 2.

In formulating the governing equations for the gas in the computational domain, the time dependent forms of the balance equations for mass, energy and momentum were used for writing ordinary differential equations (ODEs) that describe the gas in the control volumes. The balance equation for momentum was applied on a staggered mesh, i.e. to a second set of control volumes centred on the boundaries of the control volumes used for the mass and energy balances. The ODEs for the mass and energy balances were transformed into ODEs for pressure and temperature using the ideal gas equation of state. ODEs for the flow velocities were then derived from the balance equations for momentum. Asymmetric interpolation methods with filtering properties, similar to the quadratic polynomial method presented by Kühl and Schultz in Ref. [12], were



Regions of computational domain:
1: Cold cylinder volume
2, 4, 6, 8: Manifold volumes
3: Cooler
5: Regenerator
7: Heater
9: Hot cylinder volume
10: Displacer piston clearance gap

Fig. 2. Discretization of computational domain used in Stirling engine model.

included in the model to minimise numerical diffusion of quantities that are transported by advection. Artificial dissipation based on the 2nd and 4th order spatial derivatives of the flow velocities was included to dissipate acoustic phenomena with short wavelength. We have previously described [13] this method for modelling the gas more closely.

All wetted surfaces of the engine components are divided into control masses that interact with the gas filled control volumes. Most of the metal control masses correspond spatially to the gas filled control volumes, but in the displacer piston clearance gap, the control volumes that resolve the gas in the gap slide over the control masses that resolve the cylinder wall. The temperatures of the control masses containing the regenerator matrix material are modelled as dynamic, and the temperatures of all the remaining control masses are modelled as constant at their periodic steady state mean values. The periodic steady state mean values are found from the integral conditions that the net heat transfer to the control masses during one engine cycle must be zero. The control masses containing the regenerator matrix material are modelled using ODEs derived from an energy balance for a lumped control mass, i.e. a control mass with a uniform temperature. The validity of using a lumped formulation and, hence, of assuming that radial temperature gradients inside the regenerator matrix wires are not significant has been verified using a separate model that resolves the radial temperature variations inside a single matrix wire. In this study, the heat transfer rates between the gas and matrix and the flow friction were calculated using the correlations by Kühl presented by Thomas and Pittman [1].

Losses caused by flow friction and heat losses are coupled directly into the governing equations in the model by including their effects in the balance equations of the model formulation. Flow friction, for instance, is included as terms in the momentum balance equations. Heat conduction in the walls of the engine components, to mention another example, affects the energy balances of the metal control masses in the model and, hence, the temperatures of the control masses. Because the control masses interact with the gas filled control volumes through convective heat exchange, the heat conduction in the walls of the engine components is also coupled into the governing equations for the gas. Coupling loss terms directly into the governing equations breaks with more traditional Stirling engine modelling approaches, such as the approach of Uriele and Berchowitz [14], where losses are assumed to be decoupled from each other and from the governing equations and, hence, can be applied as correction terms to the calculated performance of an idealised engine.

Heat transfer and flow friction are calculated using empirical correlations for heat transfer and flow friction inside tubes, flow constraints, engine cylinders and regenerator matrices. Correlations derived for steady state conditions are used for tube flow. Approximated velocity and temperature profiles are used for calculating friction and heat transfer in the displacer piston clearance gap. The working gas and the steel in the engine are modelled with temperature dependent thermophysical properties. The bearing and seal friction forces are calculated from the forces exerted on the pistons by the gas in the engine. The efficiency of the generator is assumed to be load independent.

2.3. The simulation tool for computing steady state solutions

Periodic steady state solutions to the model were computed by formulating a boundary value problem (BVP) in the governing equations of the model and then applying the shooting method of the *MusSim* software to solve the BVP. *MusSim*, or *Multi Purpose Software for Simulation*, is a general purpose simulation tool being developed in house at the Department of Mechanical Engineering at the Technical University of Denmark. A paper describing the shooting method of the *MusSim* software has been submitted for publication [15].

2.4. Engine operating conditions

The input to the model defined operating conditions where the engine operated at 1025 rpm with helium as the working gas at a mean pressure of 7.9 MPa. The temperature profile on the outside of the heater tubes spanned between 640 °C in the ends nearest the regenerator and 760 °C near the ends that connect to the hot cylinder volume. The cooling water had an average temperature of 36 °C. These conditions are near optimal operating conditions for the SM5 engine where the engine delivers 10.7 kW of electric power with an efficiency of almost 33%.

2.5. Mapping of engine performance

The studied range of regenerator designs was defined by the range of wire diameters from 15 to 150 μm and the range of fill factors from 0.01 to 0.27 (equivalent to void fractions from 0.99 to 0.73). The mapping of engine performance was done by simulating the SM5 engine on a mesh with 72 regenerator matrix design points defined by the nine wire diameters 15, 20, 35, 50, 65, 100, 150, 200 and 250 μm and the eight fill factors 0.01, 0.02, 0.04, 0.07, 0.12, 0.17, 0.22 and 0.27. The regenerator currently installed in the SM5 engine has a wire diameter of 60 μm and a fill factor of 0.22.

2.6. Mapping of the effects of matrix temperature oscillations

The specific heat of the matrix material was varied by multiplying the temperature dependent specific heat of the stainless steel with a factor. Simulations were performed with this multiplication factor equal to 2, 10 and 100 for each of the 72 regenerator design points. Together with the simulations performed to map the performance of the engine, this yielded a total of four performance data sets for the different matrix heat capacities for extrapolating to the cases of no matrix temperature oscillations. In order to take into account deviations from linear dependence between the performance data and the reciprocal of the matrix heat capacity, the extrapolations were done in the reciprocal of the matrix heat capacity using cubic polynomials through the four data points at each of the regenerator designs. The effects of the matrix temperature oscillations on the performance of the engine were isolated by subtracting the extrapolated results for the cases of no matrix temperature oscillations from the mapping of the performance of the engine.

2.7. Regenerator design optimisation

Two optimisations of the regenerator matrix were performed using the efficiency of the engine as the objective function to be maximised. In the first optimisation, the efficiency was optimised by adjusting the wire diameter and fill factor uniformly throughout the matrix. In the second optimisation, the regenerator matrix was divided into three sections where the two end sections were each 5 mm long, leaving a central section of 51 mm. The lengths of 5 mm for the end sections were chosen for convenience; the 5 mm end sections correspond to the sections used to refine locally the discretization in the ends of the regenerator. In the second optimisation, the efficiency was optimised by adjusting the individual wire diameters and fill factors for the three sections. The optimisations were performed using a conjugate gradients method available in the *MusSim* software.

3. Results

3.1. Axial temperature profile in the regenerator matrix

Fig. 3 shows the computed axial matrix temperature profile in the regenerator currently installed in the engine at the chosen operating conditions. The matrix temperature profile is shown as the minimum and maximum temperatures reached during the cycle at the centres of the matrix control masses. A curve extrapolated to the case of infinite matrix heat capacity is also shown. Fig. 3 shows that the axial temperature profile was almost linear in the central part of the regenerator, and that the slope of the profile was slightly less steep when matrix temperature oscillations were taken into account. The figure also shows that the matrix temperatures oscillated approximately 12 °C in the central part of the matrix, and that larger temperature oscillations occurred in the ends of the matrix. In the hot end of the regenerator, the matrix temperature oscillations were as large as 70 °C.

3.2. Mapping of engine performance

Fig. 4 shows contour plots of the calculated power output, electrical efficiency, regenerator loss and heat intake of the SM5 Stirling engine for the range of regenerator designs studied. The horizontal axis in the plots represents the fill factor, and the vertical axis represents the wire diameter in the matrix. On horizontal lines in the plots, the ratio of heat transfer area to heat capacity is constant, and on vertical lines in the plots, the heat capacity is constant.

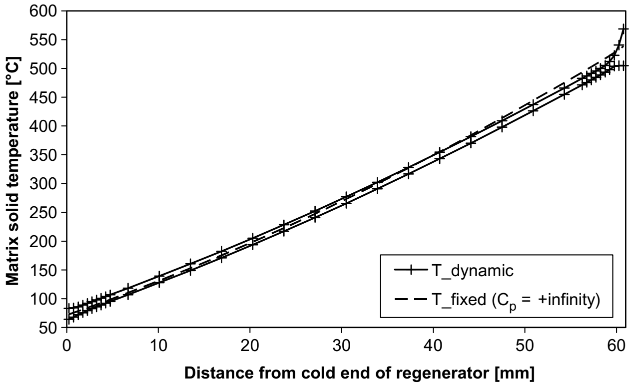


Fig. 3. Minimum and maximum matrix temperatures reached during a cycle in the current regenerator of the SM5 Stirling engine, and the corresponding matrix temperature profile for infinite matrix heat capacity.

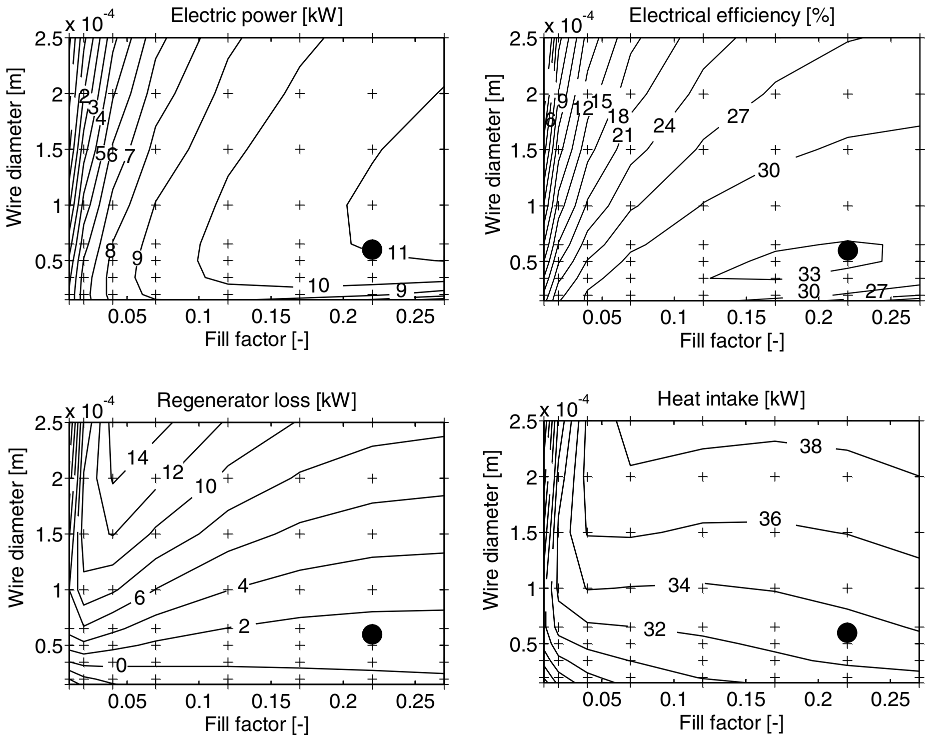


Fig. 4. Contour plots of the power output, electrical efficiency, regenerator loss and heat intake of the SM5 Stirling engine for regenerator designs with wire diameters ranging from 15 μm to 250 μm and fill factors from 0.01 to 0.27. The crosses mark the locations of calculated values. The dots mark the current regenerator design.

Fig. 4 shows that the power output from the engine decreased sharply for low fill factors and large wire diameters where the heat transfer area in the matrix was relatively small. A decrease in the power output also occurred for very small wire diameters and relatively large fill factors where the pressure drop across the regenerator was large. The contour plot for the electrical efficiency shows a peak near the present regenerator design.

For fill factors above approximately 0.07, the regenerator loss increased with smaller fill factors and larger wire diameters, i.e. with smaller heat transfer area in the matrix. For fill factors below 0.05, the regenerator loss decreased with decreasing fill factor for wire diameters above 50 μm. The heat intake of the engine showed similar trends, but for fill factors above 0.05, the variations with wire diameter were smaller in magnitude and the dependence on the fill factor was less pronounced.

3.3. Mapping of the effects of matrix temperature oscillations

Fig. 5 shows contour plots of the influences of the matrix temperature oscillations on the power output, electrical efficiency, regenerator loss and heat intake of the SM5 Stirling engine for the studied range of regenerator designs.

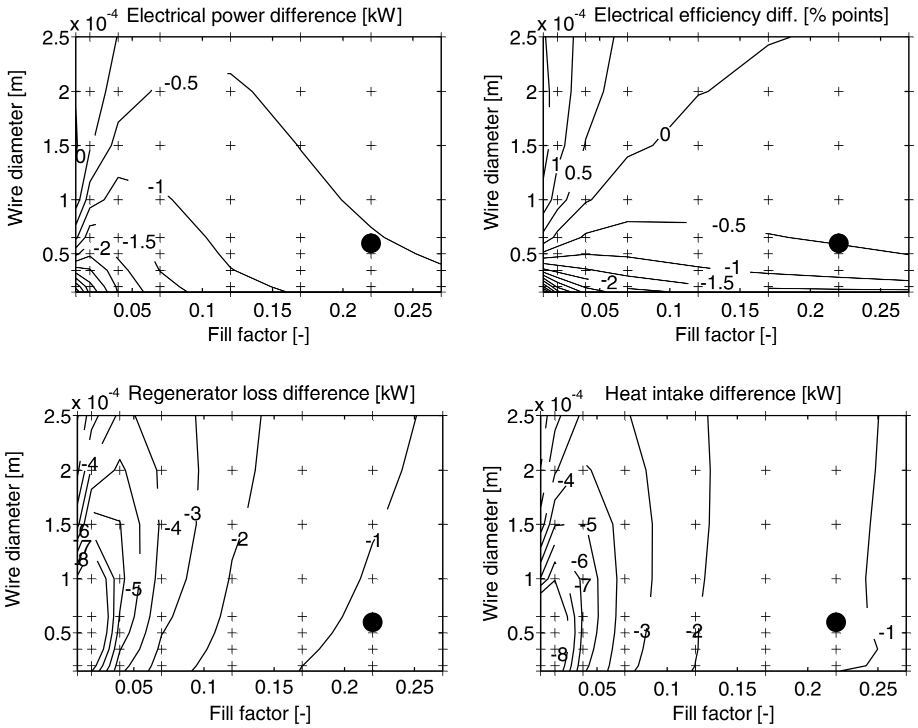


Fig. 5. Contour plots of the differences in power output, electrical efficiency, regenerator loss and heat intake for the SM5 Stirling engine caused by the matrix temperature oscillations for regenerator designs with wire diameters ranging from 15 μm to 250 μm and fill factors from 0.01 to 0.27. The crosses mark the locations of calculated values. The dots mark the current regenerator design.

Fig. 5 shows that the matrix temperature oscillations reduced the electrical power output of the engine for most of the explored regenerator designs, and that the reduction was largest for low fill factors and small wire diameters. In very sparse regenerator matrices with relatively large wire diameters, the electrical power output was slightly increased by the matrix temperature oscillations. At the current regenerator design, the matrix temperature oscillations reduced the electrical power output of the engine by approximately 5%. The electrical efficiency was increased by the matrix temperature oscillations for low fill factors and large wire diameters and reduced for larger fill factors and small wire diameters.

In Fig. 5, the plots for the differences in the regenerator loss and the heat intake look very similar, suggesting a strong coupling between them. The regenerator loss and the heat intake were reduced the most by the matrix temperature oscillations when the fill factor was low. The decrease was largest for small wire diameters.

3.4. Regenerator design optimisation

The optimisation of the regenerator where the design of the matrix was kept uniform throughout the matrix showed that the electrical efficiency could be improved by 0.1% points from 32.9%

to 33.0% by reducing the fill factor from 0.22 to 0.185 and reducing the wire diameter from 60 μm to 49 μm. This design change reduced the power output of the engine by 2% and reduced the regenerator loss by 31% from 1.15 kW to 0.79 kW.

The optimisation where the regenerator matrix was split into three sections resulted in a design with a fill factor of 0.22 and a wire diameter of 90 μm in the cold end section, a fill factor of 0.15 and a wire diameter of 36 μm in the central section and a fill factor of 0.21 and a wire diameter of 84 μm in the section at the hot end of the regenerator. With this regenerator design, the electrical efficiency of the engine was improved by 0.3% points from 32.9% to 33.2%, while the power output was reduced by 3% and the regenerator loss was reduced by 5% from 1.15 kW to 0.52 kW.

4. Discussion

4.1. The matrix temperature profile and temperature oscillations

The matrix temperature oscillations shown in Fig. 3 appear to consist of two contributions: an overall oscillation and additional oscillations near the ends of the regenerator. The overall oscillation did not bend the axial matrix temperature profile but only shifted it up and down. It would be the only contribution if the ratio of heat transfer to heat capacity was constant throughout the regenerator. The additional oscillations near the ends of the regenerator did bend the axial matrix temperature profile. They were induced when the temperature difference between the matrix and the gas flowing into the regenerator was significantly different from the temperature difference between the matrix and the gas in the central part of the regenerator. They are denoted as the inflow induced matrix temperature oscillations in the remainder of this paper. The characteristics of the shape of the temperature profile changed slightly when the fill factor was 0.01 because the cold end of the profile straightened slightly at the gas inflow temperature during inflow from the cooler.

The magnitudes and the penetration depths of the inflow induced matrix temperature oscillations depended on the design of the matrix. When the wire diameter was reduced, the heat transfer area and the ratio of heat transfer area to heat capacity were increased. This reduced the penetration depths of the inflow induced temperature oscillations and increased their magnitudes. When the fill factor was increased, the heat capacity of the matrix was increased, but the ratio of heat transfer area to heat capacity did not change. This reduced the penetration depths of the inflow induced temperature oscillations without having much effect on their magnitudes.

The magnitudes of the overall matrix temperature oscillations depended almost entirely on the heat capacity of the matrix and, therefore, on the fill factor.

4.2. The effects of matrix temperature oscillations

Fig. 5 shows that the largest decrease in power output from the matrix temperature oscillations was found for low fill factors and small wire diameters where both the inflow induced- and overall matrix temperature oscillations were largest. At the same time, the electrical efficiency was increased by the matrix temperature oscillations for low fill factors and large wire diameters and reduced for larger fill factors and small wire diameters. Hence, the electrical efficiency was increased where the overall temperature oscillations were largest and the inflow induced temperature oscillations were smallest, and vice versa. These observations suggest that the inflow induced matrix temperature oscillations had a negative influence on both power output and electrical efficiency, while the overall matrix temperature oscillations sometimes had a positive influence on electrical efficiency. Since positive effects were found, it was concluded that, of the heat pumping and the power loss due to matrix temperature oscillations documented by Jones in Ref. [6], the first could be predominant in the SM5 engine when the overall matrix temperature oscillations were large.

4.3. A new regenerator design with three sections

The optimisation of a regenerator divided into three sections showed that a notably higher electrical efficiency could be achieved than with a uniform matrix design. The optimisation yielded a matrix in which the fill factors and thread diameters in the end sections of the matrix were larger than in the central section. In this design, the ratio of heat transfer area to heat capacity was smaller in the ends of the matrix than in the central part, and the ratio was also smaller than in the optimal uniform regenerator design. The smaller ratio of heat transfer area to heat capacity resulted in smaller inflow induced matrix temperature oscillations. The central section of the matrix had a smaller wire diameter and a smaller fill factor than the optimal uniform matrix design, and this caused the overall matrix temperature oscillations in the central part of the matrix to be larger. The differences in the magnitudes of the inflow induced- and overall matrix temperature oscillations can be seen in Fig. 6. In addition to balancing heat transfer and pressure losses, the new matrix design with three sections, thus, reduced the negative effects of the inflow induced matrix temperature oscillations and intensified the positive effects of the heat pumping driven by the overall matrix temperature oscillations.

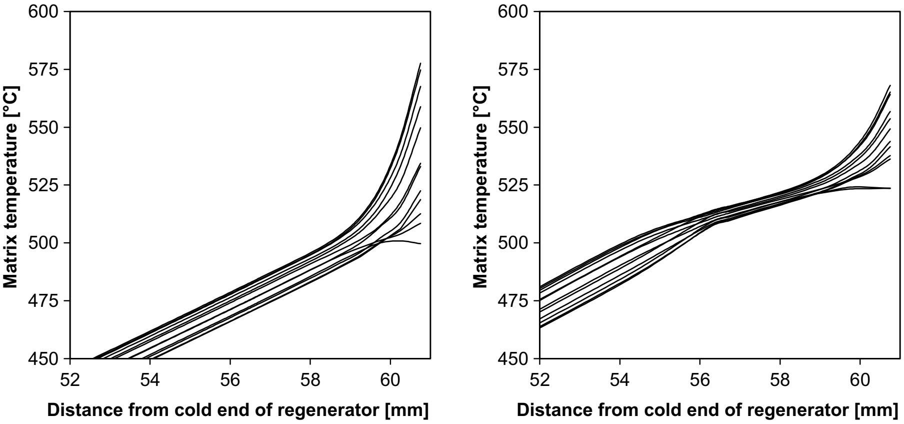


Fig. 6. Axial matrix temperature profiles in hot end of regenerator plotted every 30° crank angle for an optimised matrix with uniform properties (left) and an optimised matrix with three sections (right).

4.4. Engine performance with uniform matrix

The mapping of engine performance in Fig. 4 shows that the current regenerator of the SM5 engine is already well optimised with respect to electrical efficiency. Optimisation showed that only a 0.1% point improvement of electrical efficiency was achievable with uniform wire diameter and fill factor throughout the matrix. Fig. 4 also shows that the work output of the engine could be increased by increasing both the wire diameter and the fill factor compared to the current matrix design and that doing so would have only a moderate impact on the efficiency of the engine.

4.5. Uncertainties and the generality of the results

The largest source of uncertainty of the results was the Stirling engine model itself; the shooting method used for finding periodic steady state solutions to the model delivers accurate solutions to the model as we documented in Ref. [15]. Because the model is one-dimensional, it yields little information about gradients transverse to the main flow direction, and it cannot resolve the flow patterns in open volumes such as cylinder volumes. Heat transfer and flow friction calculations, therefore, depended entirely on empirical correlations and their accuracy for the flow conditions in the model in the simulations. The largest uncertainty in this regard was the use of steady state correlations for heat transfer and flow friction in the tubular heat exchangers. It was also not certain that transverse gradients in the flow channels of the sparsest regenerator matrices studied were properly taken into account. However, the regenerator designs that yielded optimal performance were both relatively close to the present regenerator design, where we have documented that the model accurately predicts the performance of the engine [9].

The deviations from linear dependencies between the performance characteristics for the engine and the reciprocal of the matrix heat capacities were small, and using cubic polynomial extrapolations to the cases of infinite matrix heat capacities was, thus, adequate.

It has been documented using simple axial matrix temperature profiles that heat pumping and power loss effects are caused by matrix temperature oscillations, and the same effects have been observed in models that resolve more intricately shaped matrix temperature profiles. Hence, it appears likely that the effects of, at least, the overall matrix temperature oscillations can be expected to be general and to follow the trends, such as dependence on phase angle between mass flow variation and pressure oscillation in the engine, predicted in analytical studies. It was not studied whether the negative effects of the inflow induced matrix temperature oscillations are general or if they follow some of the same trends as the overall matrix temperature oscillations. The magnitudes of the observed effects of matrix temperature oscillations will most likely be different for engines with different designs.

5. Conclusions

Using a detailed numerical model to study the existing SM5 Stirling engine, we found that the temperature oscillations of the regenerator matrix could be viewed as consisting of two contributions: an overall oscillation of a nearly linear temperature profile and additional inflow induced oscillations near the ends of the regenerator. By mapping the effects of matrix temperature oscillations, we found that, as predicted in the literature, the overall matrix temperature oscillations induced a heat pumping effect and caused a reduction of power output. When the overall matrix temperature oscillations were large, the heat pumping effect could dominate so that the efficiency of the engine was slightly improved. The inflow induced temperature oscillations were found to reduce both the efficiency and the power output.

An optimisation of a new regenerator design where the matrix was divided into three sections was performed for the SM5 engine. The optimisation resulted in the end sections having larger fill factors and wire diameters than the central section. The new design reduced the inflow induced matrix temperature oscillations and intensified the overall matrix temperature oscillations, and it improved the efficiency of the engine from 32.9% to 33.2% while causing a 3% reduction of the power output. By comparison, a maximum electrical efficiency of 33.0% could be achieved with a 2% loss of power using a uniform matrix design with a smaller fill factor and made from thinner wire than the current regenerator of the engine.

A mapping of the performance of the SM5 engine also indicated that an increase in power output could be achieved with a moderate loss of efficiency by choosing a matrix with a larger fill factor and made from thicker wire than the current regenerator.

Acknowledgments

The development of the SM5 Stirling engine is funded by the gas company Naturgas Midt-Nord, the Danish Energy Agency and the EU-Commission. The development of the simulation software used for simulating the SM5 engine has been sponsored by the gas company DONG.

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