GEOMETRIC OPTIMIZATION FOR SELF-DRIVEN PRESSURE EXCHANGE WAVE DISC

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Abstract: The efficiency of the conventional turbomachinery is small at microscale, especially that of the compressor. Adding a micro Pressure Exchange Wave Disc (PEWD) to improve the performance of a micro gas turbine has been found to be a promising solution. An initial design of a PEWD requires a motor drive it. To make it self-driven, the angled porting and curved channels were introduced to the geometric design. To find a satisfactory configuration of the porting angles and the channel curvature, with which enough energy could be extracted, an automatic optimization was performed using HEEDS combined with MATLAB, GAMBIT and FLUENT. The results indicate that the optimization was successful and that HEEDS is an effective tool to perform the task.

Keywords: pressure exchange wave disc, optimization, HEEDS, simulation

INTRODUCTION

Pressure Exchange Wave Disc

Modern technological society has an increasing need for smaller power generation devices. With the developing trend towards the miniaturization of electronic and mechanical devices, the demand for high efficiency power generation units is growing steadily. This demand is largely focused on finding a viable alternative to chemical batteries. This led to the design of micro heat engines such as internal combustion engines, gas turbines, and steam turbines that produce 10 to 100 Watts with power densities and performances comparable to their larger-scale counterparts. However, turbo-component performance suffers due to the downsizing effect. It was shown that the polytropic efficiency of conventional steady-state turbomachinery decreases with size [1, 2] because of wall effects. The continuous flow combustor suffers from increased heat loss at micro-scale, where the rate of heat loss is larger than the rate of heat production through combustion. With lower component efficiencies, the overall thermal efficiency of the micro turbine engine is significantly decreased.

Adding a micro Pressure Exchange Wave Disc (PEWD) to improve the performance of a micro gas turbine has been found to be a promising solution [3, 4, 5]. The PEWD derives from the wave rotor, but the flow is radial instead of axial. A wave disc is an unsteady flow device that is used as a pressure exchanger, employing shockwaves to transfer pressure from a high pressure fluid to a low energy fluid.

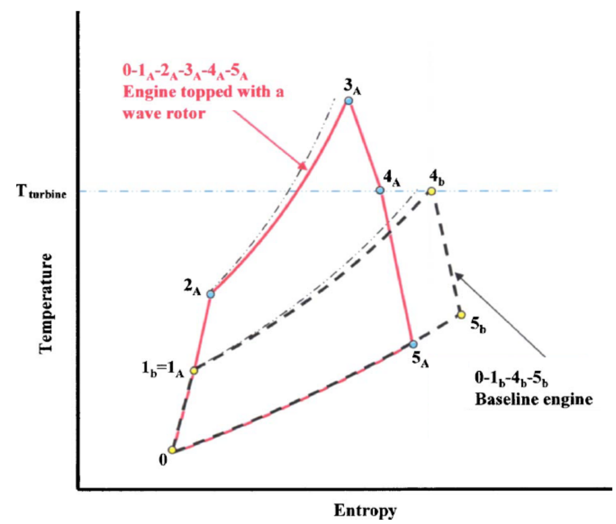

Fig. 1: Schematic T-s diagrams for a gas turbine baseline engine and the wave-rotor-topped gas turbine

The advantage provided by the wave disc is apparent when comparing a wave disc enhanced cycle with a baseline cycle. The two cycles, shown in Fig. 1, are compared for equivalent compressor pressure ratios and turbine inlet temperatures. The amount of heat addition in the combustor is the same for both cycles, and the combustion pressure loss is shown for both. The pressure increase provided by the wave disc allows combustion to occur at a higher pressure than for the baseline engine. After the pre-expansion of the exhaust gas in the wave disc, the exhaust enters the turbine at a higher pressure than for the baseline cycle. In fact, the pressure increase provided by the wave disc allows the turbine inlet pressure to be higher than the pressure at the outlet of the compressor. The larger pressure ratio across the turbine results in added work extracted from the flow. The work output increases while the input work to the compressor remains the same. This improves the cycle's thermal efficiency. The wave disc topped gas turbine engine extracts more work and is more efficient than the baseline engine.

The potential improvement of the gas turbine engine cycle provided by the implementation of a wave disc makes it an ideal candidate for micro-scale power generation. For micro-scale applications, it is necessary to achieve high thermal efficiency. With a higher efficiency, the wave disc topped engine can output more power while taking up the same space and weight.

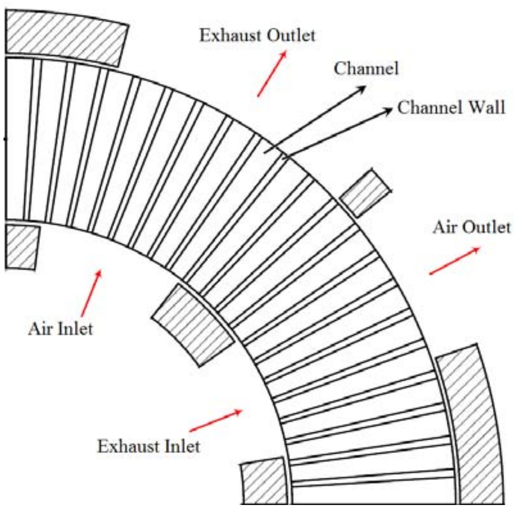

Fig. 2. Schematic of the straight channels and porting

An initial design of a PEWD may have straight channels and ports (Fig. 2), which means the flow would require enhanced angular momentum, and some energy must be added to the PEWD to drive it, usually using a motor. However, it would be beneficial to make the PEWD self-driven. Hence, modifications were made to the geometric design to allow the PEWD to extract energy from the flow to overcome the friction. These modifications include angled porting and curved channels (Fig. 3) [6].

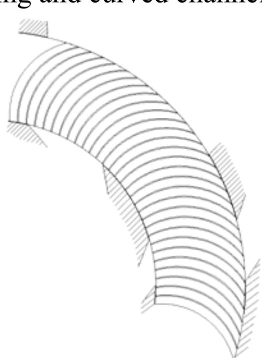

Fig. 3: Schematic of the curved channels and angled porting

To find a satisfactory configuration of the porting angles and the channel curvature, with which sufficient energy could be extracted, an automatic optimization was required.

HEEDS

In this research, HEEDS was utilized to perform the optimization, combined with MATLAB, FLUENT and GAMBIT. HEEDS (Hierarchical Evolutionary Engineering Design System) is a robust design exploration and optimization software package that accelerates the search for better and more robust design solutions within a given design space. It dramatically reduces design time by automating design evaluations. The mathematical search algorithms that the user can choose from are: Automated hybrid adaptive search (SHERPA), Genetic Algorithm, Quadratic Programming, Simulated Annealing, Response Surface, Multi Start Local Search, and Multi Objective SHERPA.

OPTIMIZATION SETUP

Since HEEDS itself cannot run the CFD simulation, it needs to be interfaced with GAMBIT and FLUENT to perform the optimization. To achieve this, an intermediate MATLAB application (PEWD.exe) was created to serve this purpose. When running an optimization: (1) HEEDS employs PEWD.exe to read the design variables from an input file, then to call GAMBIT for modeling and meshing and FLUENT to run a 2D simulation. (2) Once the simulation finishes, HEEDS reads the simulation results from the output file, (3) evaluates the performance of this design, (4) searches the design space for a better configuration, (5) generates a new input file with new values of the design variables in it, and then (6) repeats steps (1) ~ (5) as many times as required to find an optimal design.

In this work, the optimization objective was maximum power generation by the fluid. The optimization variables included the porting angles – θ_{AI}, θ_{EI}, θ_{AO} and θ_{EO}, and two parameters of the channel curvature –β_1 and β_2 (Fig. 4) [6]. The design space is tabulated in Table 1. The inner and outer radii of the PEWD are 5 mm and 7.65 mm respectively and the height of channel is 1 mm. The operating condition is tabulated in Table 2.

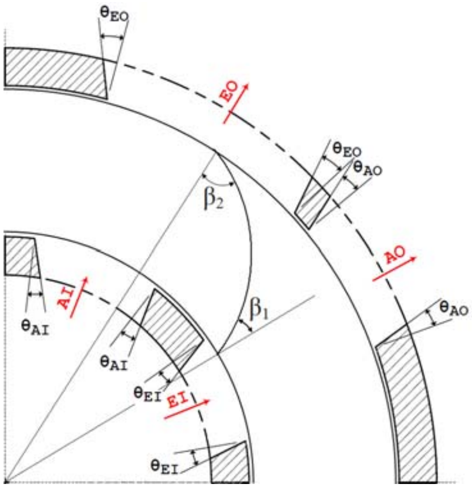

Fig. 4: Schematic of the parameters of the channel curvature and the porting angles for optimization

Table 1: The design space of this optimization

	Min	Max	Resolution
θ_{AI} (°)	0	70	0.5
θ_{EI} (°)	0	70	0.5
θ_{AO} (°)	0	70	0.5
θ_{EO} (°)	0	70	0.5
β_1 (°)	0	30	0.5
β_2 (°)	-60	0	0.5

Table 2: The operating condition

RPM	300,000
P_{EI} (Pa)	400,000
T_{EI} (T)	15,589
P_{AI} (Pa)	150,000
T_{AI} (T)	435
P_{AO} (Pa)	450,000
T_{AO} (T)	542
P_{EO} (Pa)	162,000
T_{EO} (T)	1,500

RESULTS AND DISCUSSION

The optimization ran through 78 iterations. Fig. 5 shows the progress of the optimization. The yellow dots on the graph represent the power generation of the current design. The blue curve connects the maximum power generation values found till the current iteration.

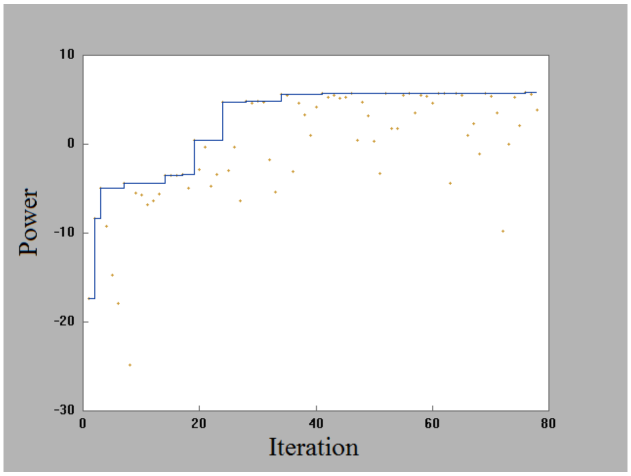

Fig. 5: The progress of the optimization

The max power found was 5.78 W which was deemed to be sufficient for the micro PEWD to overcome the friction and drive itself. The top 3 powers and the corresponding designs are tabulated in Table 3.

Table 3: The top 3 designs

Rank	1	2	3
Power (W)	5.77978	5.77490	5.75208
θ_{AI} (°)	69	70	70
θ_{EI} (°)	64.5	63.5	63.5
θ_{AO} (°)	17	11	69.5
θ_{EO} (°)	0	0.5	0.5
β_1 (°)	30	27	27
β_2 (°)	-59.5	-60	-60

Fig. 6 (a) ~ (c) show the variation of the design variables with the power generation. In Fig. 6 (a) it can be found that the power increases with θ_{AI} and θ_{EI}, and the max power occurs when the θ_{AI} is around 70° and θ_{EI} around 64°. Fig. 6 (b) shows that the power increases as θ_{AO} decreases and the max power occurs when θ_{AO} is 0°, whereas the relationship between θ_{EO} and power is not clear, the reason for which might be that the optimization process was not fully complete. Fig. 6 (c) shows that the power increases as β_1 increases and β_2 decreases, and the max power occurs when β_1 is around 30° and β_2 around -60°, which means the more curved the channel, the higher the power.

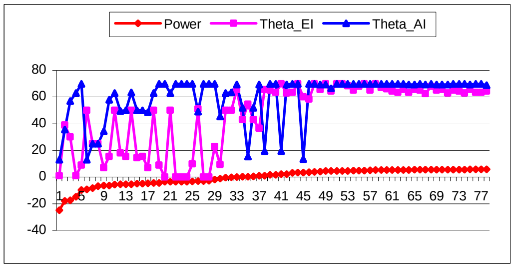

Fig. 6 (a): The variation of the inlet porting angles with power

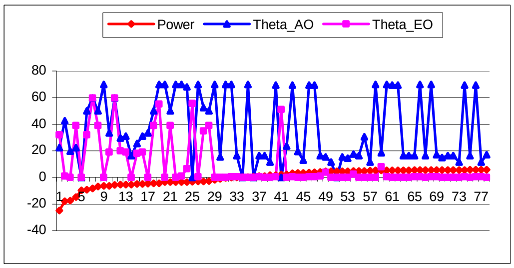

Fig. 6 (b): The variation of the outlet porting angles with power

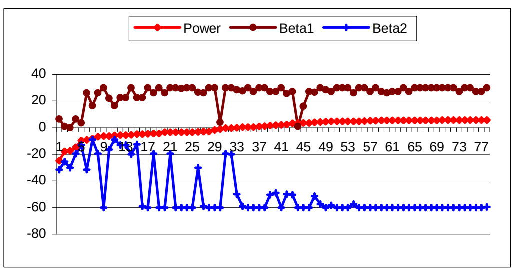

Fig. 6 (c): The variation of the wall angles with power

CONCLUSION

The MATLAB code was successfully developed to interface HEEDS with GAMBIT and FLUENT. An automatic optimization was performed using HEEDS. The porting angles and the wall angles were chosen to be the optimization variables and the maximum power generation to be the objective. The maximum power found after 78 iterations is 5.78 W when θ_{AI} = 69°, θ_{EI} = 64.5°, θ_{AO} = 17°, θ_{EO} = 0°, β_1 = 30° and β_2 = -59.5°. For this micro PEWD, such power is sufficient to overcome the friction and drive itself. The results indicate that HEEDS is an effective tool for such an optimization. The results show potential for micro power generation.

REFERENCES

[1] Epstein A H 2003 Millimeter-scale, MEMS gas turbine engines *Proc. ASME Turbo Expo 2003* 16–19.

[2] Müller N, Fréchette L G 2002 Performance Analysis of Brayton and Rankine Cycle Microsystems for Portable Power Generation *ASME International Mechanical Engineering Congress & Exposition (New Orleans, Nov 17-22, 2002)*

[3] Iancu F 2005 Integration of a Wave Rotor to an Ultra-Micro Gas Turbine (UμGT) *Doctoral Dissertation* (Michigan State University)

[4] Iancu F, Akbari P, Müller N 2004 Feasibility Study of Integrating Four-Port Wave Rotors into Ultra-Micro Gas Turbines *40th AIAA/ASME/SEA/ASEE Joint Propulsion Conference and Exhibit (Florida, 2004)*

[5] Iancu F, Piechna J, Dempsey E, Müller N 2005 Ultra-Micro Wave Rotor Investigations *Proc. PowerMEMS 2005 (Tokyo, Nov, 2005)* 93-96.

[6] M. Vagani 2008 Design Considerations for Micro Wave Disc Engines *Master Thesis* (Michigan State University)