Development of Rotary Wankel Devices for Power Generation

Ghada A. Sadiq
Mustansiriyah University, College of Engineering, Mechanical Engineering Department, Baghdad, Iraq

ghadaanbas@uommustansirya.edu.iq

Abstract. Rotary Wankel engine has been the subject of the research since it is introduction; it can work as combustion engines as well as compressors and expansion devices (turbine). A volumetric expander is an appropriate device used in a steam Rankin cycle for low power generation, consolidated heat, and power unit. Wankel expansion devices have significant advantages, such as compactness, almost no vibration, low cost, and noise. A computational fluid dynamics (CFD) is extended to be used ANSYS-Fluent 17.2 for simulation the flow in a single stage rotary expansion device and to investigate the expander’s power. The current study is compared with the published work (Mazda) for the volumes and power output of the rotary expansion devices and showed a good agreement. Wankel expander size of 118.5 mm radius of the rotor, the eccentricity of 17 mm, and rotor width of 69 mm is selected. Results showed the contours of pressure and temperature at any rotor angles to insure the design is performing as suspected. The power output is 27.416 kW for ports without valves while by using valves only in the inlet ports created 17.8 kW.

1. Introduction

The demand for power generation is rapidly increasing due to population increase and global warming. Renewable energy is the solution to solve the problem overlooking climate changes by using various energy heats sources, for example, solar energy, wind energy, biomasses, low temperature geothermal, and waste heat recovery.

The simplicity of the Wankel rotary design is the foremost reasons for interesting in the Wankel engines for vehicles application. For the same power output, Wankel engines are more compact, less vibration, and cost than a piston internal combustion engine [1]. The rotary Wankel expander has been studied for steam Rankine-cycle systems by Badr et al. [1] of rotor-radius 131.4 mm for Curtiss-Wright, and 118.5 mm rotor-radius for Mazda with shaft rotational speed of 3000 rpm. A computer-aided-design technique was selected to reach the optimal design, and the port's location of the expander is reported. Combinations of both lubrication and material were presented. Results showed that the mass flow rate of steam was 0.12 kg/s and power production of Mazda rotary expansion devices was 16.8 kW at 3000 rpm shaft rotational speed. The Wankel rotary engines performance was investigated by the same group Badr et al. [2] working as an expander in steam Rankin-cycle for Curtiss-Wright and Mazda engines. An individual study has been adjusted in choosing the locations of ports produced 5-20 kW at 3000 rpm shaft rotational speed. Also, Badr et al. [3] displayed the benefits of applying the rotary engine as an expander device operating as a mini combined heat and power unit. The comparison between Wankel expansion devices with helical-screw, turbines, and rotary vane was described. Results illustrated that the screw expander’s rotational speeds were higher than the working
speeds of some of the driven gear necessary drop gearbox and speed-control equipment. Also, helical-screw expansion devices need a proportionately high quality of production and high cost. Therefore, Wankel expansion devices are considered to be the most appropriate device for the presentation suggested.

An experimental and numerical investigation on the Wankel expansion devices was analysed by Antonelli et al. [4-7]. Results displayed that close agreement was obtained from the numerical and the experiments using compressed air. Different working fluids were studied and calculated the efficiency and power output for various temperatures and working fluids. Results presented an isentropic efficiency of about 85%. Organic Rankine Cycle efficiency about 10% was obtained by pentane. Also, a Wankel expansion device by steam was examined using modelling software AMESim. A reduction in steam specific consumption of 25% was obtained with multistage Wankel expansion devices.

CFD modelling was studied the performance of the Wankel expansion devices by Sadiq et al. [8]. Several Wankel expansion devices for both single stage and two stages using various configurations were studied at different boundary conditions. Combining two Wankel expanders created 8.52 kW equated with single stage produced a power around 4.75 kW at 6 bar and 400 K inlet pressure and temperature at 7500 rpm. Furthermore, (91%) and (87.25%) isentropic efficiency were obtained of two and single stage respectively.

CFD is an efficient tool for accurate (3D) to simulate and optimize the fluid flow of the rotary Wankel expander using ANSYS-Fluent. In this study, 3D CFD modelling was investigated to study the performance of a rotary expander due to the limitation of published work with various operating conditions using steam as working fluid.

2. Modelling of Wankel expansion device

The expansion device contains the epitrochoid housing, the rotor housing, and the eccentric shaft, as shown in Figure 1. The moving parts (rotor and shaft) are organised by two spur gears (the exterior gear placed on the side of the housing, and the internal gear is placed inside the rotor) for specific connection between the rotor tip and the housing [8, 11]. The rotor and flanks are organised mainly using the radius of the rotor \( r \) and an eccentric rotational shaft \( e \). The rotor translates over the eccentric shaft and rotating around the centre itself with one revolution while the rotational shaft finalises three revolutions around the eccentric circle [8, 11].

![Figure 1. Definitions of Wankel geometry.](image)

The housing equations are:

\[
\begin{align*}
x_h &= e \cos 3\theta + r \cos \theta \\
y_h &= e \sin 3\theta + r \sin \theta
\end{align*}
\]  

The rotor equations are:

\[
x_r = r \cos 2\nu + \frac{3e^2}{2r} (\cos 8\nu - \cos 4\nu) \pm e \left(1 - \frac{9e^2}{r^2} \sin^2 3\nu\right)^{\frac{1}{2}} (\cos 5\nu + \cos \nu)
\]  

\( \theta \): eccentric angle of the rotor, \( \nu \): eccentric angle of the tip, \( r \): rotor radius, \( e \): eccentricity.

\( \theta \) and \( \nu \) are the eccentric angles of the rotor and the tip, respectively. The eccentric radius \( e \) is the distance between the rotor and the centre of the housing.
\[ x_r = r \sin 2\nu + \frac{3r^2}{2r} (\sin 8\nu - \sin 4\nu) \pm e \left(1 - \frac{9r^2}{r^2} \sin^2 3\nu\right)^{1/2} (\cos 5\nu + \cos 3\nu) \]  

(4)

Where \( \nu = \left[ \frac{\pi}{2}, \frac{5\pi}{6}, \frac{11\pi}{6}, \frac{13\pi}{6}, \frac{19\pi}{6}, \frac{21\pi}{6} \right] \)

3. Computational fluid dynamic (CFD)

The CFD is used for investigating fluid flow rapidly and usefully. ANSYS Fluent 17.2 Software was used to tolerate the mesh dynamically changes with the time required for the motion of the Wankel expansion device geometry [10]. User defined functions (UDF’s) were used to generate the accurate movement and applied in Fluent to deliver the precise necessary mesh movement, specified a favourite rotational speed [8, 11].

Tetrahedrons mesh type was used for 3D Wankel geometry with 62000 nodes and 300000 elements. In Fluent solver, some assumptions were considered in the numerical computations as 3D real flow and piecewise-polynomial specific heat, no slip on the wall boundary and adiabatic conditions, inlet pressure and temperature of 6 bar and 431.5 K, and outlet pressure and temperature of 25000 Pascal gauge pressure and 293 K. Table 1 shows the details of the geometry of Mazda Wankel engine used in this study.

| Table 1. Wankel expander details. |
|-------------------------------|-------|-------|-------|
| r (mm) | e (mm) | b (mm) | a (mm) |
| 118.5  | 17    | 69    | 4     |

The diagram of pressure-volume (P, V) was produced from fluent results, permitting the calculation of appraised work through each ‘chamber’ for every revolution. The power is calculated using equation (5). The trapezoidal function in MATLAB [12] is used to give the enclosed area created by (p-v) curve, as shown in equation (7) [8, 11].

\[
\text{Power Output} = \text{Work} \times \text{Output shaft speed} \\
\text{Work} = \text{Area enclosed the curve (p,v)} \\
\text{Area under the curve} = \text{trapz}(p,v)
\]  

(5)  

(6)  

(7)

4. Results and Discussion

Figure 2 shows a comparison among the current study (CFD) and Badr et al. [1] for the commercial Mazda Wankel engine of 118.5 mm radius of rotor, the eccentricity of 17 mm, and 69 mm of rotor housing width for expected expansion device volume at different angles [8].

![Figure 2. CFD compared with Badr for expander’s volume among rotor angle [1, 8].](image-url)
The power was achieved to reach 16.8 kW and 17.8 kW for Badr et al. [1] and CFD, respectively, as shown in Figure.3 with a difference about 6% at the same operating conditions [8].

![Figure 3. CFD and Badr et al. power output results [1, 8].](image)

Figure 4 illustrates the contours of pressure for (r = 118.5, e = 17, b = 69, a = 4) mm of 6 bar and 431.5 K, inlet pressure and temperature at 3000 rpm. It can be seen the contours for the rotational angle to confirm the model is performing as estimated.

![Figure 4. Shows the contours for absolute pressure.](image)

Figure 5 illustrates the contours of total temperature at the same operating conditions above. The figure shows the difference in temperature depending on the rotor rotating inside the housing. The maximum temperature lies in the minimum volume and decreasing in the expansion part.
Figure 5. Shows the contours for total temperature.

Comparison between the Wankel expander with and without valves at inlet ports was investigated as shown in Figure 6. The power output produced is 27.416 kW compared to 17.8 kW without and with valves, respectively. The valves were used in the inlet ports to control the inflow of the working fluid because each chamber has two suction and two exhaust phases in the same period.

Figure 6. Wankel expansion device with and without valve at inlet ports.

5. Conclusion

An investigation describing the CFD ANSYS Fluent is successful in using the geometry of Wankel rotary engine as expanders to generate the power for calculation the power output and show the contours of absolute pressures and total temperatures through rotating the rotor in the housing to confirm the model is working as anticipated. Good results were achieved from the evaluation between the current work, and the published work for both volumes and power output for Wankel expander size ($r = 118.5$, $e = 17$, $b = 69$) mm. Results showed the power output is 27.416 kW for inlet and outlet ports without valves while by using valves in the inlet ports only created 17.8 kW.
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