DEVELOPMENT OF EFFICIENT STATIC SHAFT WANKEL EXPANDER FOR ORGANIC RANKINE CYCLES

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ABSTRACT

The Organic Rankine Cycle (ORC) presents one suitable solution to the utilisation of low grade heat from some renewables and waste heat from industrial and power generation processes. However, the efficiency of the ORC will be dependent on the efficiency of the expansion device. The Wankel expander shows promise because the disadvantages of the combustion engine are lost when used as an expansion device. Furthermore, it has the advantages of few moving parts, a high power to weight ratio, low noise and vibrations and simplicity in design and manufacture. However, to achieve a good efficiency, an external valve setup is usually required. This paper presents an alternative form of the Wankel expander in which this is not required and the desirable simplicity is maintained. To analyse this expander computational fluid dynamics was utilised. The simulation results gave a maximum isentropic efficiency of 85% (2bar inlet gauge pressure, 6000RPM, 245W). The case with the maximum power gave 572W (3bar inlet gauge pressure, 9600RPM) but only achieved 73% efficiency. The performance of the expander was then compared to other expanders from literature, where it faired comparably in terms of efficiency and as it has greater simplicity, it could be preferred in many applications.

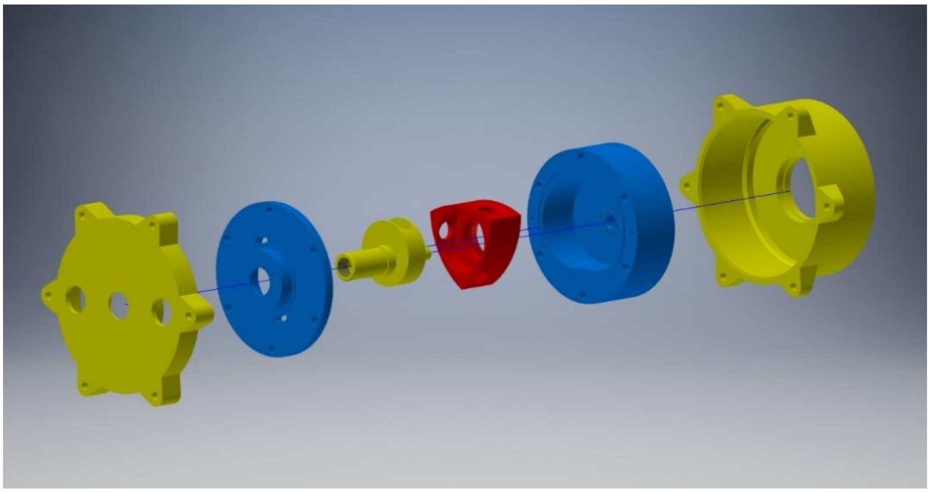
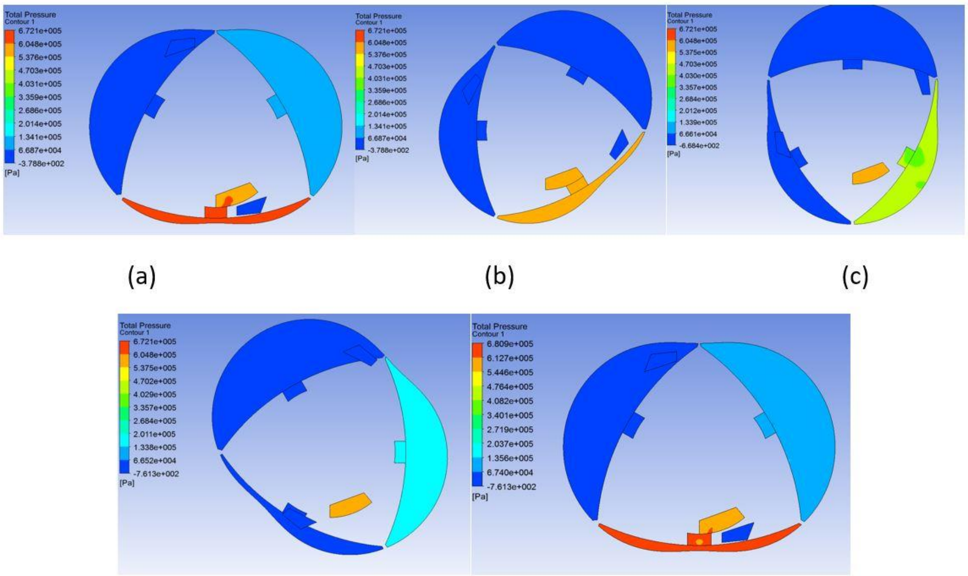


Figure 1: Exploded CAD view of static shaft Wankel expander

1. INTRODUCTION

The past decades have seen an ever increasing demand for energy. Combined with the problems caused by burning fossil fuels, the need for alternative methods to harness renewable energy sources and increase the efficiency of current power generation has become paramount. The Organic Rankine Cycle (ORC) has the advantage of operating on low grade heat sources, such as waste heat from industrial processes or power generation and renewable sources such as geothermal and concentrated solar.



(a) (b) (c)

(d) (e)

Figure 2: Different stages of operation of the static shaft Wankel expander (shown with CFD pressure)

A key component of the ORC is the Expansion device. The performance of this component has a significant effect on the overall ORC performance (Qiu et al., 2011, Ziviani et al., 2013). Volumetric expanders are advantageous as they better handle two-phase conditions that may occur at certain times. Turbines, screw, scroll, reciprocating piston, rotary vane and gerotor expanders have been analysed for use in ORC (Dumont et al., 2017, Ziviani et al., 2014, Saghlatoun et al., 2014), however, none of these comparisons include the Wankel expander which could offer particular advantages.

The Wankel expander is named after Felix Wankel, who invented the geometry (Wankel, 1963) and designed the first engine of this kind. The most well-known use of the geometry was in Wankel combustion engines. However, due to its characteristics, it is much more suitable as an expansion device (Antonelli and Martorano, 2012). The advantages of both the Wankel engine and expander include a high power to weight ratio, small number of moving parts, low noise and vibrations, low cost and simplicity in design, manufacturing and maintenance (Badr et al., 1991). The Key disadvantages of the Wankel combustion engine was the lubrication of the internal seals and the subsequent burning of that lubricant. This would not be the case for an expander in a closed cycle, as combustion does not take place and there are not emissions to be concerned about.

The combustion engine does not need valves, as the inlet port can be open for the entire inlet phase. However, the expander requires the inlet to be cut-off at a certain point to allow for the most efficient expansion (Antonelli et al., 2014). Therefore, one of the remaining disadvantages of the Wankel geometry as an expansion device, is the need for valve-controlled inlet ports. This will increase the size and complexity, subsequently increasing the cost of manufacture and maintenance. This paper looks at computational fluid dynamics (CFD) modelling of an alternative form of the Wankel expander that provides an intrinsic method to better control the inlet cut-off, removing the need for external valves.

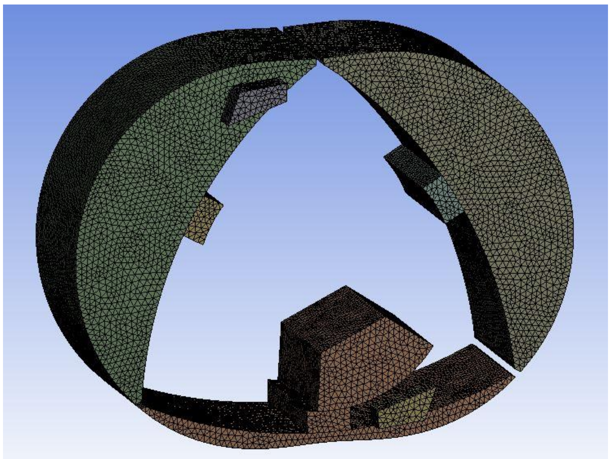


Figure 3: Mesh produced for CFD simulations

2. WORKING PRINCIPLE

To differentiate it from the conventional Wankel expander, the alternative form of the Wankel expander will henceforth be referred to as the static shaft Wankel expander. The static shaft Wankel expander takes inspiration from the DKM Wankel engine designed by Felix Wankel. As the name suggests, the shaft in this design remains stationary and fixed to the outer casing. Therefore, to achieve the correct relative movement, the internal rotor and the housing must both rotate. The rotor and housing parts rotate about two different parallel axes, which correspond to their own centre of mass and are offset from each other by the Wankel geometry's eccentricity value. The inlet ports can no longer be placed on the side of the housing because it rotates. Therefore, the inlet flow comes through the centre of the static shaft and enters the Wankel expander's 'chambers' via holes in the rotor flanks. The flow outlet ports can be located on the housing side or periphery as with the conventional design and the outlet flow is captured by the outer casing. Figure 1 shows an exploded CAD view of the static shaft Wankel expander to demonstrate the design. The yellow represent the stationary parts, whilst the blue and red parts both rotate, but at different speeds. Figure 2 shows CFD pressure contours at different stages during a cycle, to help outline the working principle.

Table 1: CFD setup and Expander parameters

Parameter	**Value**	**Parameter**	**Value**
Solver	Transient Pressure-Based	**Inlet conditions**	1,2 & 3 bar gauge pressure, 360k temperature
Models	Energy equation, k-e turbulence	**Outlet conditions**	0 bar gauge pressure, 300k temperature
Solution method	Coupled	**Ambient pressure**	1bar absolute
Working fluids	n-Butane, n-Pentane (both modelled as real gases with Peng-Robinson equations)	**Wall conditions**	No slip, adiabatic.
Wankel radius and eccentricity	r = 30mm, e = 4.125mm	**Wankel expander width**	20mm

The first advantage of this design, is that both the rotor and housing parts rotate around their own centre of mass. This removes the requirement for the balancing masses that conventional Wankel devices require. The second advantage is that because the inlet flow enters through the shaft, its opening timing can be controlled much the same as a valve-controlled port. This allows the optimum cut off ratio to be designed into the device.

3. METHODOLOGY

This study used the CFD software Ansys Fluent 18.2 to model the static shaft Wankel expander. To achieve this, the geometry of the expander was created in the CAD software Autodesk Inventor, after which it was imported in Ansys's proprietary meshing software. The mesh for the CFD was created at this point, including naming the bodies and faces of the mesh and creating the necessary interfaces between them. The mesh used for the model is shown in Figure 3.

After the mesh was completed it was imported into Fluent, here the boundary conditions, solver settings, output files and the mesh motion were setup. The setup details are given in Table 1. For the mesh motion, user defined functions (UDFs) were utilised. UDFs are written in C language and can control various aspects of Fluent in ways that are not intrinsically available. Therefore, these UDFs move the mesh nodes of either the rotor or the housing faces. Both are simply rotated about their own centres of gravity, but the housing rotates 1.5 times faster than the rotor.

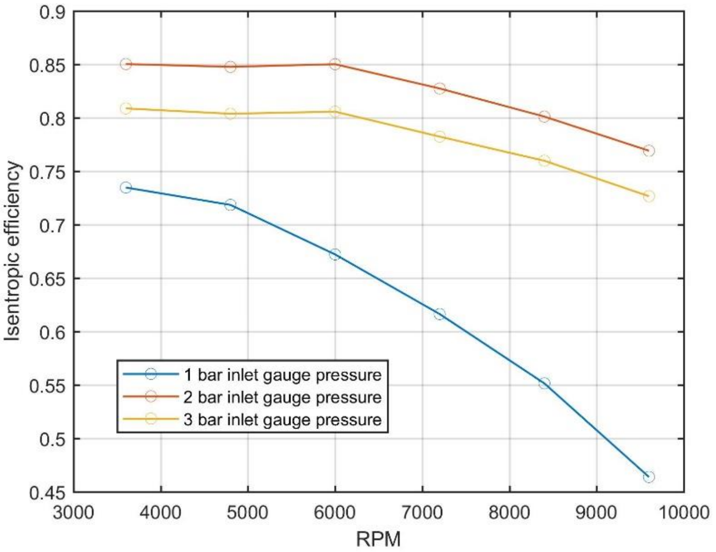


Figure 4: Isentropic efficiency against rotational speed for n-Butane at different inlet pressures

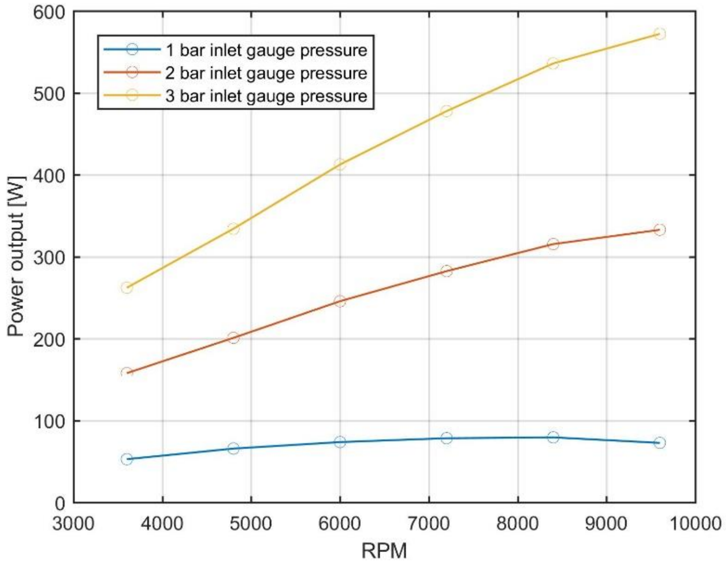


Figure 5: Power output against rotational speed for n-Butane at different inlet pressures

Once the simulation has run, the pressure, volume and flow results are read into Matlab, where a pressure-volume diagram is created. Using this, the enclosed area is calculated, which is equal to the work done in an expansion event. This can be used to find the power output and isentropic efficiency, given the rotational speed and the inlet mass flow rate.

n-Butane and n-Pentane were chosen as the working fluids to initially analyse this design, as they are both commonly used in ORC systems and are both readily available to use in Ansys Fluent 18.2. In previous works, a similar CFD model of a conventional Wankel expander had a grid independency study which showed little variation past 150,000 elements (Sadiq et al., 2017), therefore this was used for the grid density in this case as well. Previous work also validated the conventional Wankel expander CFD model experimentally (Sadiq, 2018), allowing the CFD results in this paper to be held in some degree of certainty.

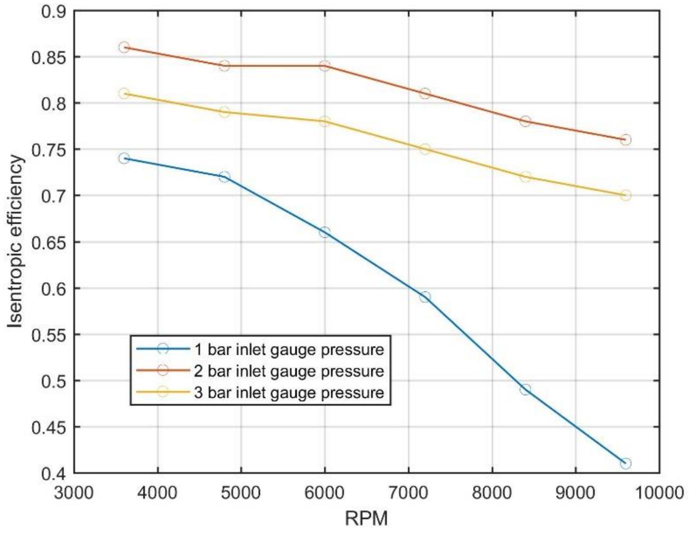


Figure 6: Isentropic efficiency against rotational speed for n-Pentane at different inlet pressures

4. RESULTS AND DISCUSSION

Figure 4 shows isentropic efficiency curves for the n-Butane working fluid. It is clear that 2bar is the best inlet gauge pressure in this case. However, the static shaft Wankel expander is easy to redesign for a different optimum inlet pressure, by simply changing the angle the inlet is open for. The maximum efficiency of 85% remains almost constant between 3600RPM and 6000RPM. This is useful if the expander would be likely to undergo speed fluctuations. Figure 5 shows that the 3bar inlet gauge pressure produces the highest power output over the range and that at higher rotational speeds the power output is also larger. The best case at 85% efficiency (2bar inlet gauge pressure, at 6000RPM) gives 245W, which is significantly lower than the maximum of 572W. However, at the maximum power of 572W (3bar inlet gauge pressure, at 9600RPM) the efficiency is 73%, which may not be acceptable in some applications. One option would be to select the 3bar inlet gauge pressure at 6000RPM, which has 80% isentropic efficiency and 413W power output.

Figure 6 show the efficiency curves for n-Pentane. It is noticed that the trends are much the same as for n-Butane, however, the efficiency curves drop faster as the speed is increased. For this expander, under these operating conditions, n-Butane would be the working fluid of choice.

To assess how this expander fairs when compared to other expanders, efficiency values were gathered from various literature sources and compared in Figure 7. It can be seen that the efficiency of the static shaft Wankel expander has about 20% higher maximum than the conventional Wankel expander without valves and in fact is very similar to the Wankel expander with valves plus the scroll expander and screw expander. There is also still room for further optimisation with the static shaft Wankel expander which would bring the efficiency higher still.

The static shaft Wankel expander can therefore compete with other established expanders in efficiency. It is much simpler to design and manufacture than the scroll expander, screw expander and the Wankel expander with external valves and would therefore be cheaper and quicker to produce. This would prove useful in allowing ORC systems to become more widespread in use.

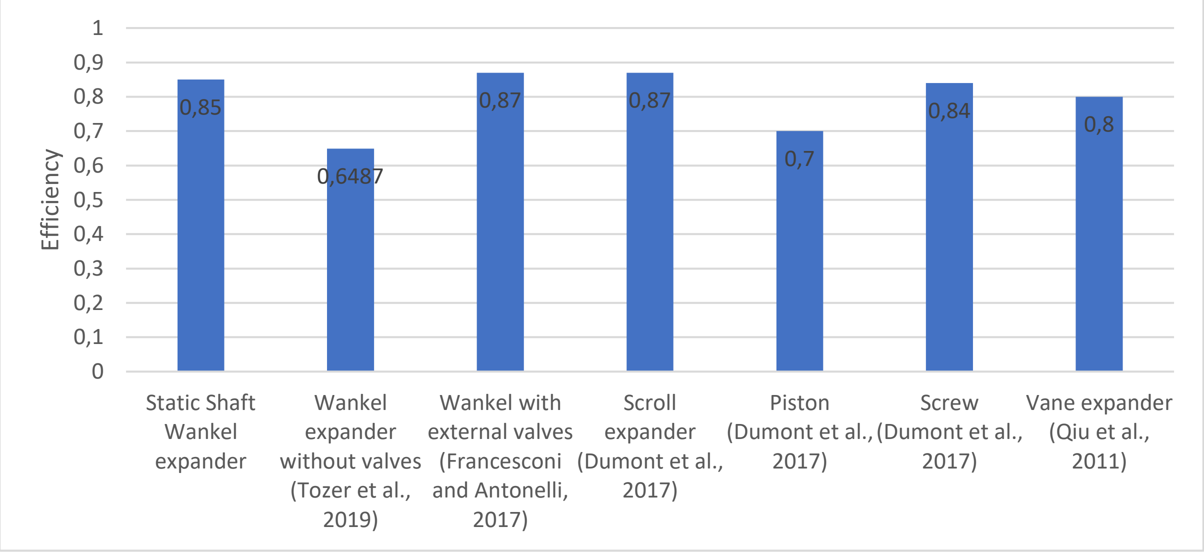


Figure 7: Comparison of expanders from literature

5. CONCLUSION

The static shaft Wankel expander was introduced in this paper. The main advantage of this expander over the conventional Wankel expander, is its ability to better control the inlet timings and therefore, control the cut-off ratio. Using CFD with n-Butane and n-Pentane as working fluids, the performance of a static shaft Wankel expander was simulated. The results found that n-Butane consistently produced the best results in terms of efficiency. Amongst the n-Butane results, the best inlet gauge pressure for efficiency was 2bar at 85%, closely followed by 3bar at 80%. However, the 3bar inlet gauge pressure provided 1.6 times higher power output, so it may be preferred, especially if it is for a compact or small scale system. The rotational speed for maximum efficiency has a range between 3600RPM and 6000RPM for both the 2bar and 3bar cases. This large range would be useful for applications which have varying load demands. Finally the expander's efficiency was compared to various other expanders from literature, including a Wankel expander with an external valve setup. The static shaft Wankel expander performed well comparing to the top expanders and has the advantage of greater simplicity when compared to them.

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