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Design Module for the Industry

Design and development of a novel gearless Wankel-like mixer-pump –

The Lau-Wan mixer

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Abstract This paper discusses a case study of a process that provides a holistic design experience by integrating two independent project modules of an undergraduate degree programme. The project proposed by an external party involves the design, manufacture and testing of a scaled prototype for microfluidics applications. The systematic and integrated approach described in the same format as the students' project report resulted in a novel gearless Wankel-like pump that provided visual results that compare well with the external party's numerical studies.

Keywords mechanical engineering design, Wankel engine and pump, integrated approach

Introduction

Engineering design is a very important core element of basic mechanical engineering education. Very often students complete the design process with a conceptual design or at best a product that has little opportunity to be tested, much less a new design that is fully endorsed by the client.

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This paper describes the process and outcome of the design education starting from client's specifications to the development and the successful evaluation of a novel product. The process is in two stages: a group stage bringing out the prototypes from the concepts, and the individual stage bringing out the product from the prototype. Throughout this particular process, students and staff actively engaged the clients in discussions, and in the process learnt about the work of computational and experimental fluid mechanics.

The engineering design process is a part of the Newcastle University (NU) Mechanical Design and Manufacturing Engineering (MDME) undergraduate programme offered under the Singapore Institute of Technology (SIT) initiative. It provides opportunity for students to work on projects offered by the industry. For this project, the clients are computational fluid dynamics (CFD) scientists from the Institute of Higher Performance Computing (IHPC), a research laboratory with A*STAR.

The scientists have used CFD simulations to investigate the applications of Wankel-like pumps in microfluidic mixing. They had characterised the mixing performance of a micro scaled Wankel-like pump with a 2-apex rotor turning in a 1-lobe epitrochoid shaped chamber. Their CFD simulations have predicted microfluidic mixing in the micro mixer. Their prime motivation for this project is for the team to design and fabricate a scaled up Wankel-like pump for experimentation.

At the end of the 2-semester design process, a novel gearless Wankel-like pump for mixing, called the LW mixer pump prototype was produced. Experimentally recorded flow visualised results showed a mixing of two viscous fluids that potentially could be used to support the numerical characterization of such pumps. The LW mixer works like a Wankel pump except that it has fewer and less complex parts – it does not need gears associated with Wankel engines or pumps; and it has a simple channel to prevent hydrostatic lock. These features make it possible to be manufactured as a low cost microfluidics device.

This article is organised and presented in almost the same manner as a design process, with outcomes at each stage described in terms of the learning outcomes. For brevity, the required product will be referred to as a mixer in the article.

Background - the Microfluidics mixer

Microfluidic devices and mixers have made considerable impact in the fields of biomedical engineering as in diagnostics and drug development over the years. For such devices to be useful the mixing should be effective and the device as simple as possible so as to reduce the cost of the products. Microfluidic mixing achieves a thorough and rapid mixing in small scale devices. It can be achieved by increasing the contact area and contact time of the fluid species using specially designed microchannel configurations, or by enhancing the diffusion effect between the different species flows. In other instances, external energy or force is applied to perturb the sample species to

encourage mixing through diffusion. A review of microfluidics mixing is given by CY Lee *et al*¹.

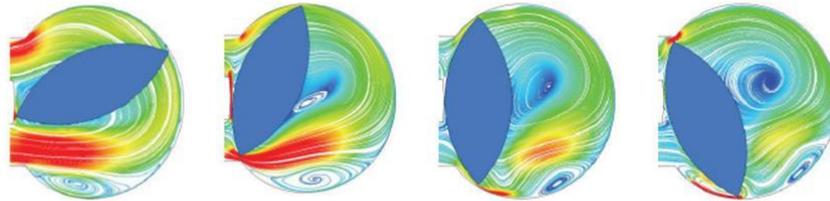


Figure 1: Streamlines on a plane (Taken from S Wan *et al*², 2014)

Wan *et al*² had been investigating the use of Wankel-like pump in microfluidics applications. They found from CFD simulations that a 2-apex rotor turning at low speed in 1-lobe epitrochoid shaped housing is able to generate vortices at Low Reynolds Number and hence has the potential to improve mixing. One set of their 3D simulation results for a pump with rotor centre-to-rotor tip length of $R = 0.01$ m is shown in Figure 1. The largest dimension of this simulated mixer-pump is 0.025 m (2.5 cm).

Producing a physical micro scale Wankel-like pump to generate results for comparisons with their computational studies will be useful, but fabricating a micro scale engine or pump is often associated with micro-electromechanical systems (mems) process^{3,4,5}. However, as explained to the project team, flow visualisation of the mixing process in a scaled up mixer prototype can be similarly useful. In essence, both scales of the mixers can be characterised by some relevant dimensionless number such as the pump Reynolds number so that similar flow conditions can be replicated in both the

micro scale simulations and the prototype. Comparisons between CFD results of the micro mixer and the properly scaled up mixer prototype will then be meaningful.

The Problem Statement

Even though a scaled prototype is to be designed, the design and the operations of the prototype have to be simple *such that it can be replicated at the micro scale and* that the micro mixer can be produced at a relatively low cost. The relevant parameters of the prototype have to be selected to give the same Reynolds Number as that used in the micro scaled mixing simulations.

The Objective

To design an active Wankel-like mixer that facilitates mixing and flow visualisation of the mixing of two fluids of similar viscosity.

Literature review

The students' basic literature search focused on a review of the Wankel engine and its working principles. The objectives are to understand (a) how the engine and the pump work and from these investigations, understand how a micro mixer can be designed and be built to meet the design requirements; and (b) the geometry of the epitrochoid envelope and its implications in the design of a rotary pump.

The Wankel engine⁶ has few moving parts: the rotor turning eccentrically about an axis in a 2-lobe combustion chamber, an eccentric output shaft and a pair of annular and

pinion gears. The rotor annular gear turns about the stationary pinion gear affixed to the chamber cover. The gear ratio between the pinion gear and the annular gear of 2:3 ensures that the rotor makes a $\frac{1}{3}$ turn about its axis for every 1 turn of the eccentric output shaft and that the 3-apex triangular shaped piston turns within and touches the 2-lobe combustion chamber at its three apexes at every instance of rotation.

The Cora Rotary Pump, by Monties *et al*⁷ shown in Figure 3 is an example of a Wankel-like pump. It works almost the same as the engine except that it has a 2-apex rotor turning in a 1-lobe chamber, and that it is driven by a brushless dc motor via an input eccentric shaft. The ratio of rotor annular gear to the stationary pinion gear is now 2:1 so that the rotor turns $\frac{1}{2}$ a revolution for every 1 revolution of the input shaft. It has no reciprocating motion and with a diameter of 94 mm and a height of 60 mm, it is small enough to be implanted as a ventricular assist device in circulatory support systems.

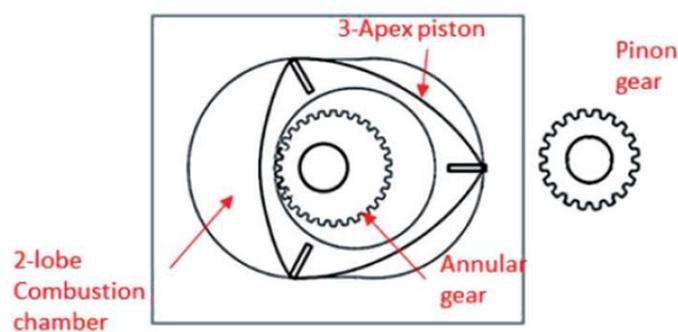


Figure 2: A Wankel Engine Schematic

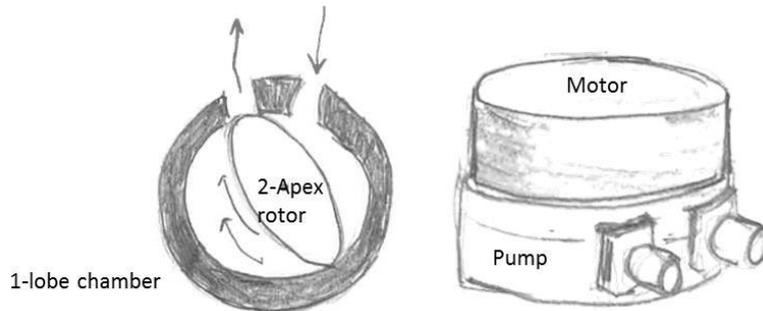


Figure 3: Cora Pump schematic and the implant (Taken from Monties *et al*⁷)

In both the Wankel engine and the Cora pump, the chamber wherein the piston or rotor turns has a profile of an epitrochoid. The coordinates of the epitrochoid is given by the equation

$$x = e \cos(m\theta) + R \cos(\theta)$$

$$y = e \sin(m\theta) + R \sin(\theta)$$

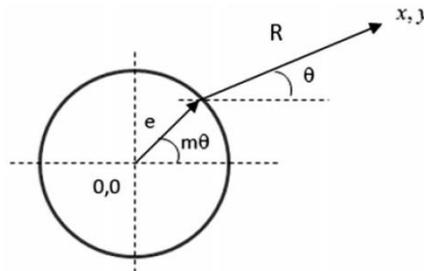


Figure 4: Epitrochoid generating parameters e and R .

Where R represents the rotor centre-to-rotor tip distance; e , the eccentric (offset) distance of the rotor centre to the axis of a rotating shaft (the Origin of the epitrochoid), and $m\theta$, where m is an integer, is the instantaneous angle of rotation of the rotating

shaft. For example, for the Cora pump with a 2-apex rotor, $m = 2$, and for the piston of a Wankel engine, $m = 3$.

For convenience, $2R$ will be referred to as the length of the major axis of the rotor, and e is the eccentricity. The rotor centre rotates on a circle of radius e .

Whether as a pump or as an engine, the basic Wankel-like design has these parameters given in Table 1:

| # of chamber lobes | # of rotor apexes | Gear ratio | Speed ratio |
|--------------------|-------------------|------------|-------------|
| 1 | 2 | 1:2 | 2 |
| 2 | 3 | 2:3 | 3 |
| M (an integer) | M+1 | M:M+1 | M |

Table 1: Taken from Leemhuis & Soedel⁸, 1976

Although the objective is to design a scaled up prototype, the eventual need is for a micro mixer. Hence the geometric dimensions must be sensitive to this need. Two main problems associated with micro mixer that has bearing on the prototype design are:

- (a) With a 2-apex rotor of major axis of length 2 cm, the synchronising gears are likely to be very small, especially the pinion gear required;

(b) Unlike the 3-apex Wankel rotor, a 2-apex rotor has a smaller mid-section area to accommodate the (offset) eccentric shaft making it difficult to adopt the conventional Wankel engine concept of using synchronising gears.

Design Specifications – key parameters (Table 2)

| Parameters | Requirements | Quantifiable values |
|--------------------|--|---------------------|
| Input | Low speed motor | 200 rpm |
| Rotor | 2 apexes Major axis length ($2R$) | $R = 0.04$ m |
| Flow visualisation | Plane of fluid species flow | |
| Fluid species | Two, of similar viscosity | |

Table 2: Design Specifications

Geometrical analysis of the 2-apex mixer in a one lobe epitrochoid

To understand the effect of the prototype size on the micro mixer, a geometric model of the epitrochoid was carried out using $e = 0.003$ m and $R = 0.01$ m. These are values used in a CFD simulation of a 2-apex micro-mixer shown in Figure 1. Two different pairs of synchronisation gears are shown (Figure 5) for the same rotor; the rotor is shown as an ellipse.

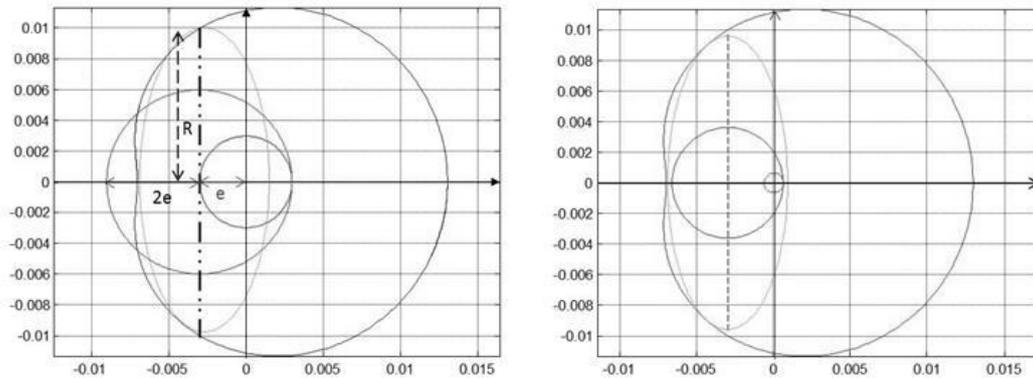


Figure 5: geometrical modelling of a 2-apex rotor in the epitrochoid geometry

The largest dimension of the mixer is 2.5 cm. The gears must give a $\frac{1}{2}$ turn of the rotor for every turn of the eccentric input shaft. If the pinion gear has a radius of $e = 3$ mm, then the annular gear has to have a radius of 6 mm. Two problems are presented: the annular gear is larger than the minor axis of the rotor; and it is difficult and expensive to fabricate the pair of gears of those sizes. Making the annular gear smaller (as shown on the right diagram) will result in a different gear ratio and speed ratio, and an even smaller pinion gear.

Given the e and R values, many design iterations were tried to arrive at designs of the annular and pinion gears to achieve the gear ratio of 2:1 and to simultaneously fit the annular gear into the rotor. In addition, the pinion axis is to be collinear with axis of the circle of radius e , and its radius constrained by the difference: (annular gear radius $- e$), and it will be costly for microfluidics applications to use mems technology to fabricate the mixer.

A simpler solution was found by observing the rotor angular positions as the input shaft rotates. The positions of the rotor at different angles are represented by lines of the major axis of length $2R$ with each of these lines centred at the respective points on the circumference of the circle of radius e (left diagram of Figure 6).

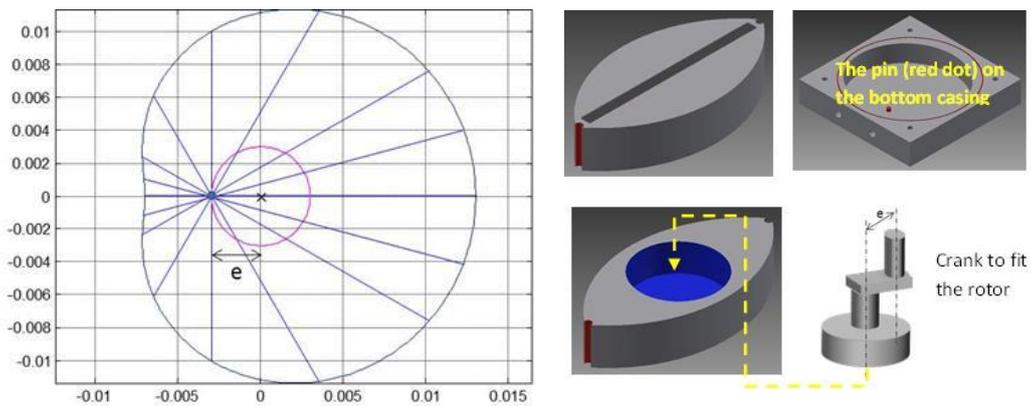


Figure 6: Rotor at various positions and 3D drawings of rotor, crank and bottom cover.

As the rotor turns, its major axis passes through the point $(-e, 0)$, shown as a dot, with respect to the Origin of the epitrochoid as shown in the left diagram of Figure 6. Relative to the rotor, this point slides along the major axis as the rotor turns. An animation using the CAD drawing for the rotor was also done and shown in Figure 7

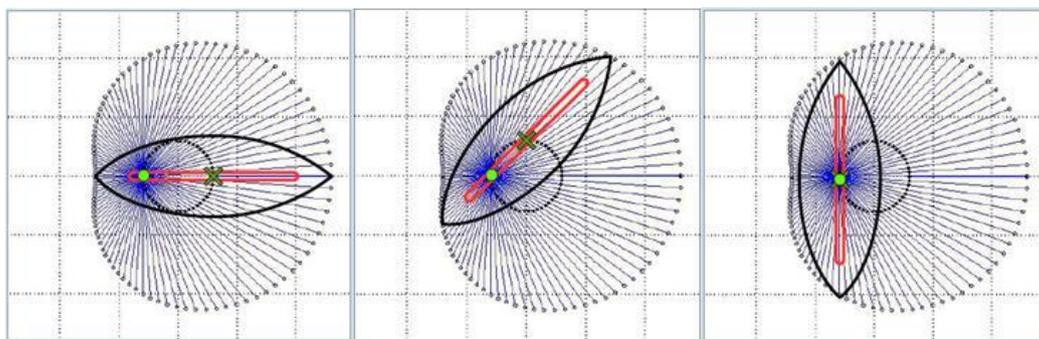


Figure 7: animation of the rotor as seen from the bottom

Hence a cheap and simple way of rotating the rotor can now be designed. It involves inserting a pin on the bottom cover and a groove on the underside of the rotor to constraint the rotation of the rotor to touch the epitrochoid at the two apexes, and a crank, similar to that used in a well to draw water. The critical dimension is the eccentricity e between the input shaft axis, through the Origin of the epitrochoid, and the axis of the centre of the rotor. Designs of these are shown on the right diagram of Figure 6.

3D Printing of the prototype parts

The final stage of the design is the embodiment of the product. To allow for flow visualisation and for comparison with CFD simulations, the scaled up prototype has values of $R=0.040$ m and $e =0.012$ m. The overall mixer size is now about 0.1 m. For pedagogical purpose, both the gears and the crank and slider mechanisms for the scaled up prototype were 3D printed. The process enables the team to better understand design and manufacturing, and with the assembled product, to better understand the working principle of their pump design.

The printed gears (Figure 8) have poor tolerances and do not meet the ratio of 2:1. The mixer does not work well – the rotor turns but does not contact the edge of the chamber as it turns.

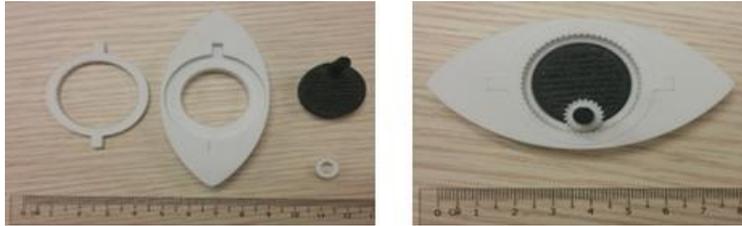


Figure 8: 3D printed gears and rotor for the mixer pump.

The printed parts for the pin-slider and crank mixer pump are shown in Figure 9.

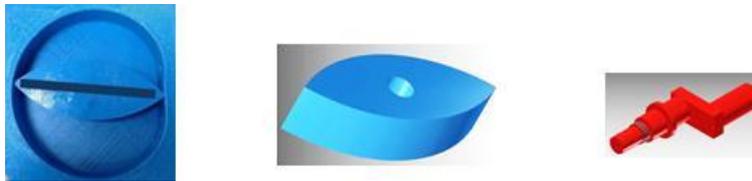


Figure 9: 3D printed prototypes

The assembled 3D printed crank and pin-slider prototype is turned by hand.

Constrained by the slide and pin, every revolution of the rotor requires two turns of the input crank and at every instance of rotation, the rotor touches the epitrochoid at its two apexes. The rotary pump meets the parameter constraints of a Wankel engine without a pair of annular and pinion gears.

The Prototype

The process of material and components selection is followed through. Due to the requirement for flow visualization, the physical model will be built with acrylic and mounted above a camera. The final design of the prototype was then outsourced for production (Figure 10).



Figure 10: The scaled up prototype (Taken from An Ning *et al*⁹, 2015)

This last stage links theory and practical. The outcome is both a learning experience in terms of proper communications (design drawings) with the manufacturer and the realisation (by the team) that the designs are always lacking somewhat in details. Two main criticisms revealed by the first prototype are: (a), the lack of seals at all conceivable places – between the casing and the covers, the bearing, crank shaft interface chamber, and at the apexes (hence the two grooves at the apexes for the seals were added as shown in Figure 5) and (b) the hydrostatic lock causing the torque required to turn the rotor to increase significantly, effectively jamming the rotor when the volume of the incompressible fluid is reduced towards the outlet. The latter occurs when the volume in the chamber between the outlet and a tip (B, nearest the outlet) becomes very small. It is then difficult to turn the rotor to squeeze the fluid out through the outlet.

Seals were effectively put into the respective places and the leakages were substantially minimised. The hydrostatic lock was overcome by a simple solution – the

creation of a hydraulic channel in the casing between the outlet and the rotor tip B as shown in Figure 11

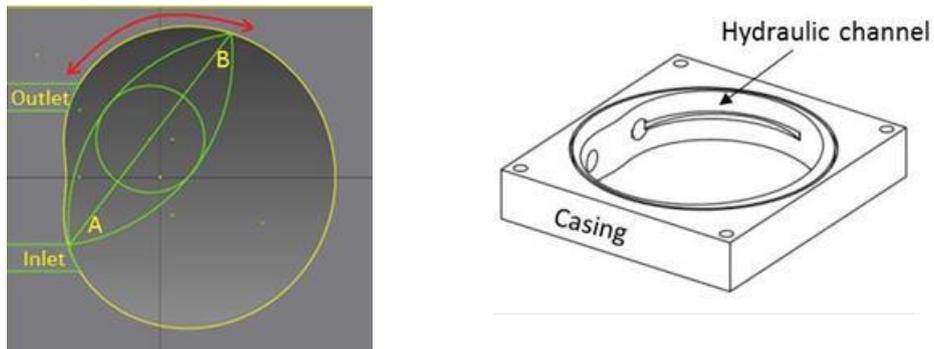


Figure 11: The hydraulic channel

As the fluid volume near the outlet decreases, the hydraulic channel allows the built up pressure to be relieved. This keeps the torque almost constant for the rotation.

Experimental Setup

This part of the process allows the team to evaluate the effectiveness of the prototype. The inlet and outlet connectors, control valves and motor were installed. Two bottles containing slightly diluted detergent were used as the fluid species. One of the species is dyed red. A Y-joint is used to feed the two fluids into the inlet. After a few turns, as more of the fluid species are drawn into the mixer, the inlet and outlet are shut whilst allowing the fluid species to recirculate (Figure 12).

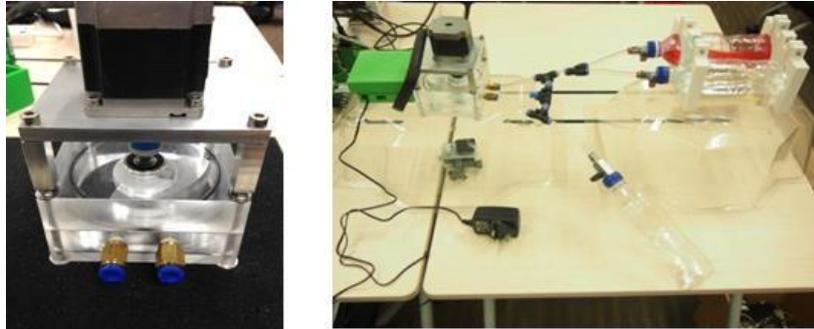


Figure 12: The LW-mixer in the experimental setup

Experimental results

A camera was placed below the mixer. As the rotor rotates, the mixing process was captured on video. The computed Reynolds Number shows that the flow is laminar. The results¹⁰ are in Figure 13:

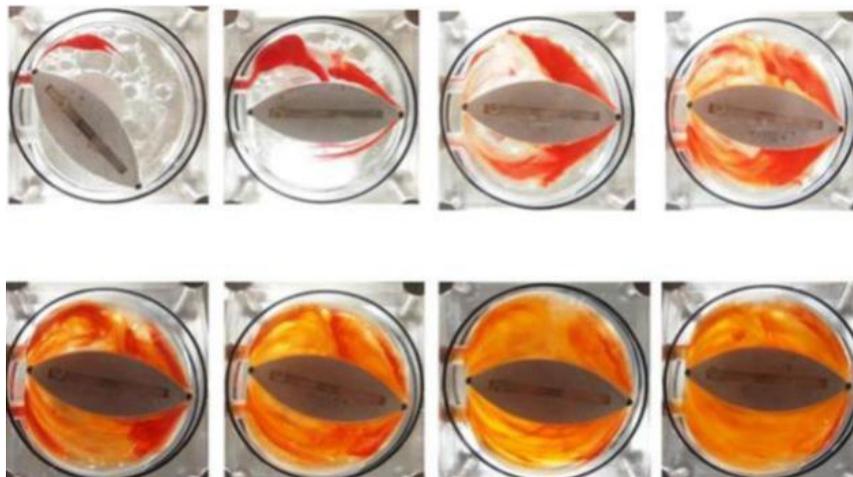


Figure 13: The mixing results after 8 revolutions – view from top to bottom and left to right (Taken from An Ning¹⁰, 2015)

The mixing process can be observed in stages as the rotor turns. The flow is quite comparable to that given in Figure 1, albeit at a larger scale.

Discussion

The integrated design modules allow the students to work through the various stages of a design life cycle, and provide the opportunities to put into practice what they have learnt in other mechanical engineering modules. Through literature review, modelling of the geometry of the pump and the use of 3D printing, they are able to identify the critical design aspect of the design and arrive at a new design of the Wankel-like pump that can be cheaper to manufacture for microfluidic mixing. Computer animations of the geometrical model help to confirm the workability of the design.

A couple of important aspects stand out: having a realisable end product and the involvement of an external party, the industrial partner. The former means that a design that meets the clients' requirements has to be realised within the design cycle and getting it right as early as possible in the process is necessary. Outsourcing the prototype to manufacture completes the design education with the need to produce standard engineering drawings for the manufacturer. Rework is expensive. In addition, students learn to communicate with the clients through discussions, sketches and drawings and in this particular exercise, take back lessons on practical aspects of fluid pumps operations and design. Lastly, working with physical items made from 3D printing is a great help in the design and prototyping process. Parts would be 3D printed

and assembled and the prototype verified that the concept is workable. However, it is possible that students tend to rely too much on 3D printing and perform less engineering, especially kinematics, analysis.

The results obtained from experimentation with the prototype showed that the mixing of fluid species in laminar flow in the plane of the rotor can be achieved. They have been accepted by the client. The results have also prompted them to explore the modification of the design to observe flow mixing in planes perpendicular to the rotor and in improving the efficiency of mixing using cascaded mixers. The latter can be easily achieved with this design.

Conclusion

The modules have provided the students with an opportunity to design and realise a prototype based on the clients' requirements. They provided students with opportunities to work together as a team, to actively engage with staff and the clients. In addition, many other aspects of their mechanical engineering education were actively used in arriving at a new design that possibly could mean an affordable microfluidics device. At the end of it, a novel gearless Wankel like mixer prototype had been developed and tested. It can be manufactured in a smaller scale at a relatively low cost.

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Declaration of Conflicting Interests

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