# Prototype Bench Test: Dec 5th 2019

Open/Closed Loop Air Cycle Proof of Concept

## Introduction

In September 2019 FeTu produced a tiny air cycle unit for exhibition purposes, it has served its purpose well in explaining and demonstrating the operation of the FeTu principle. With events of 2019 complete there was a hope to test the unit with Avid technology as part of our IDP14 A/C compressor study but as the year draws to a close and with a full program at Avid, the opportunity for such has passed.

Before deciding if we should commit further resource to the potential of FeTu performing as a ‘compander’ (an integrated compressor/expander), it seemed sensible to run a crude ‘proof of concept’ test to verify if reality aligned with the outcomes of our beliefs & analytical studies.

The FeTu ‘compander’ was tested Open Loop (Section 1) and Closed Loop (Section 2).

## 1. Open Loop

This section details the findings when rotational power is applied to drive the unit, recording instantaneous pressure and temperature information within an ‘open loop’ system, with a single link pipe that joins the two volumetric domains. A simplistic heat exchanger formed part of the link pipe enabling heat subtraction or addition.

Depending on the drive direction, the system will operate as a heater or cooler as depicted in Figures 1 & 2 below.

The derived results will be compared to isentropic conditions where the index ‘γ’ is 1.4 (for air). This condition refers to having zero heat addition so will not physically occur in the real tests therefore the theoretical temperature and pressure differentials will always be higher than reality.

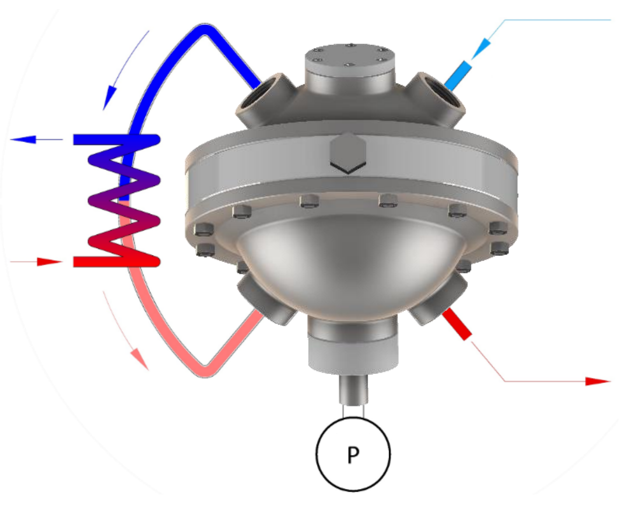


**Figure 1**: The FeTu Open ‘Cooler’ Cycle

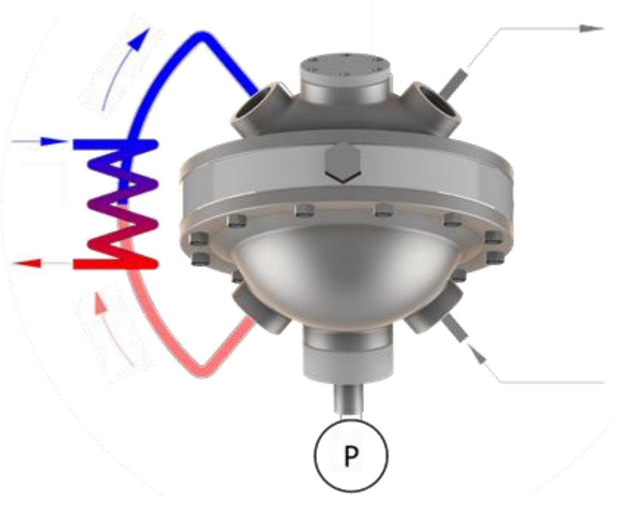


**Figure 2**: The FeTu Open ‘Heater’ Cycle

## 1.1. Testing Strategy

A makeshift test stand was set up on site at FeTu, utilising an 84mm FeTu compander with 2 x 15.7cc (non-drive side) & 2 x 23cc (drive side) chamber volumes. Utilising two Omega absolute pressure transducers and two thermocouples – depicted in Figures 2 and 3 respectfully, the data was logged using an Omega data recorder. For convenience and health & safety reasons a battery powered drill was used as the prime mover. A handheld tachometer recorded the speed.

As pictured in Figure 4, the exchanger carried the air moving from the 15.7cc to the 23cc chamber volume as a 'Cooler' and the 23cc to the 15.7cc as a 'Heater'. One complete cycle was performed every 180° of rotation. External conditions were stationary room temperature air.

**Figure 2**: Omega Pressure Transducer Probe

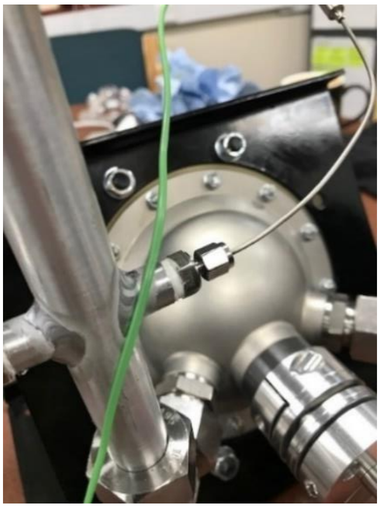

**Figure 3**: Thermocouple probe

**Figure 4**: Heat Exchanger/Test layout

## 1.2. 'Cooler' Test

Whilst running the device as a cooler, two things were expected to happen; a drop in pressure in the link pipe (heat exchanger) due to a polytropic expansion, and subsequently a drop in temperature as such. Figures 6 and 7 depict such pressure and temperature plots, via the sensors inserted into the air stream at probe points seen in Figure 5. The readings are compared with isentropic conditions (zero heat addition) for when $\gamma$ is 1.4.

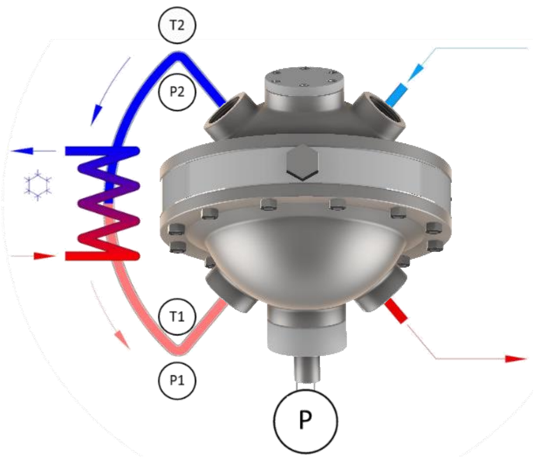


**Figure 5**: 'Cooler' Test Configuration

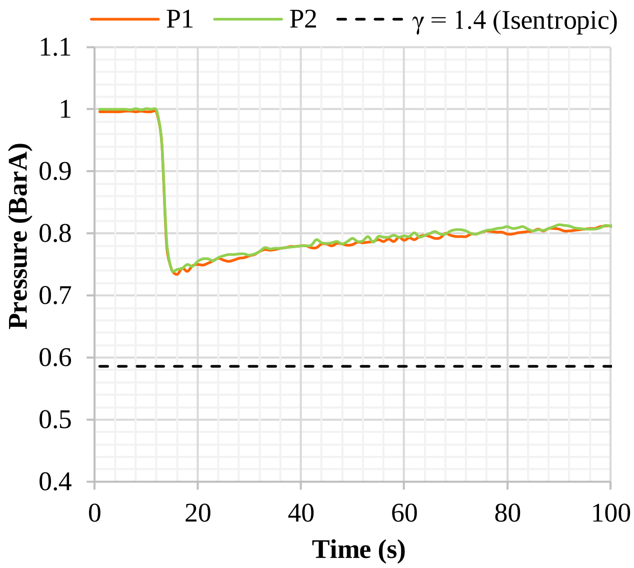


**Figure 6**: 'Cooler' Pressure performance

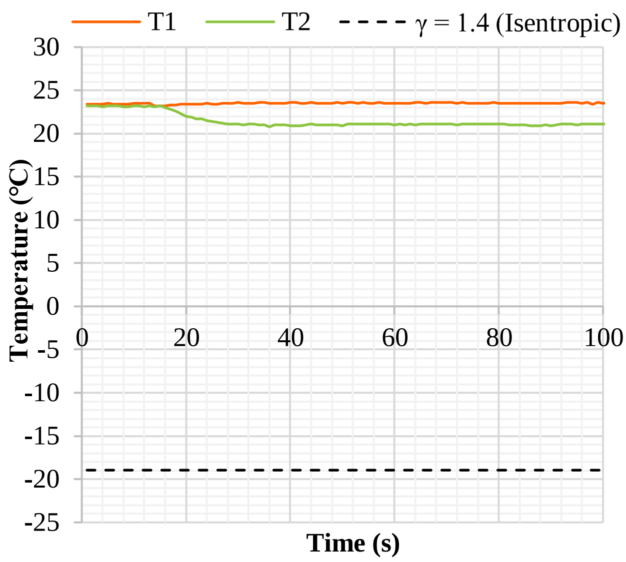


**Figure 7**: 'Cooler' Temperature performance

### 1.2.1. Observations:

Both pressure and temperature reacted immediately upon the unit being rotated at 16 seconds; at 800rpm we had predicted 40 revolutions for pressure stabilisation, this was realised as factual on test. As expected, temperature was slower to trend due to the thermal inertia of the machines material.

There is a substantial pressure drop within the heat exchanger due to the 'companding' nature of operation, the expansion allowed the air to drop to 0.74BarA at 800rpm. Due to the power/speed loss to the drill, the affective PR drops to 0.8BarA. It is also noted that P1 and P2 follow an identical trend meaning that the small heat addition across the exchanger has little impact on the pressure.

A 3°C temperature delta was recorded (down from room temperature), quite disparate from isentropic conditions which is likely due to heat addition from the exchanger and internal machinery. It is clear that a larger volume ratio, greater flow or lesser thermally reactive heat exchanger is needed to affect a bigger temperature drop, to follow suit from the pressure gradient.

### 1.2.2. Tech summary (without oil):

a) Running Speed: 800 rpm then drop
b) Temperature Delta: 3°C
c) BIVR: 1.464
d) Pressure Ratio: 1.25-1.351
e) Oil free
f) Pressure Stabilisation at 40 revs
g) Polytropic Index: 1.015

### 1.3. 'Heater' Test

Whilst running the device as a heater, two things were expected to happen; a rise in pressure in the link pipe (heat exchanger) due to a polytropic compression, and subsequently a rise in temperature as such.

Figures 9 and 10 depict such pressure and temperature plots, via the sensors inserted into the air stream at probe points seen in Figure 8. The readings are compared with isentropic conditions for when γ is 1.4.

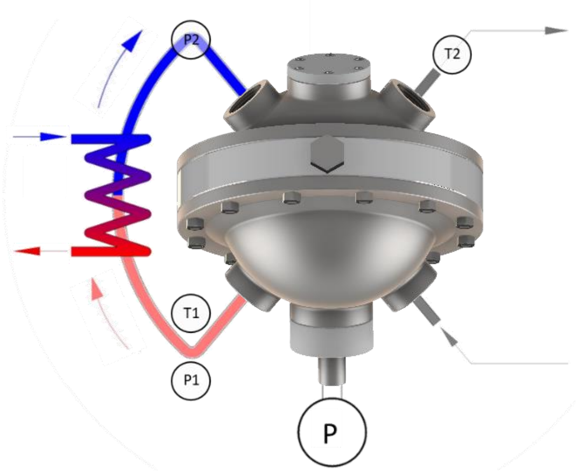


**Figure 8**: 'Heater' Test Configuration

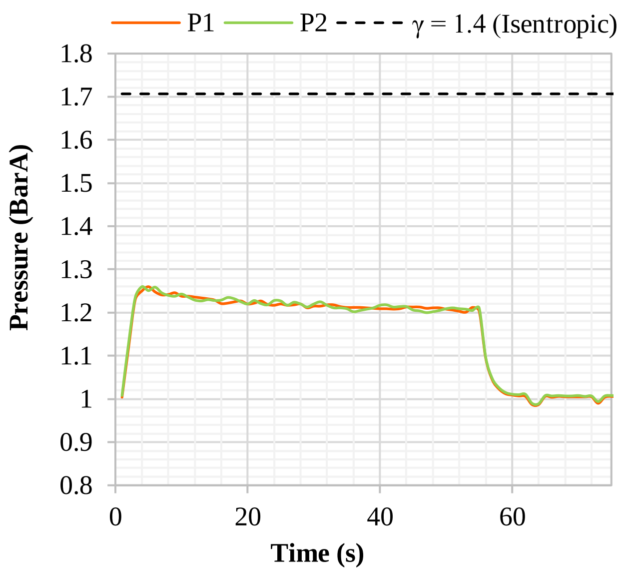


**Figure 9**: 'Heater' Pressure performance

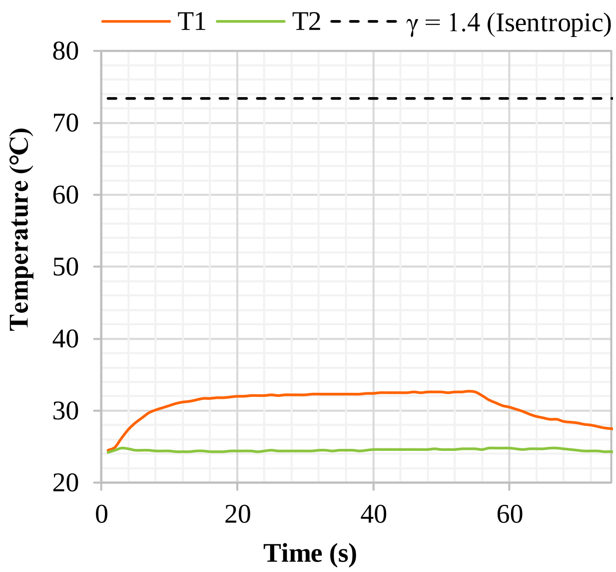


**Figure 10**: 'Heater' Temperature performance

#### 1.3.1. Observation

Both Pressure and Temperature again reacted in a manner as expected, pressure reacting instantaneously and to a settled value in approximately 3 seconds (40revs at 800rpm), whilst just as cooling the temperature settled after 15-20 seconds due to the heat exchangers thermal inertia.

The Pressure reached a peak of 1.26 BarA, identical and opposite to the reverse: 'Cooler'. Again, P1 and P2 probes across the heat exchanger read identical values.

The T2 probe was moved to the exit port to observe the effect. The effect was that the open air cycle exhausts room temperature air, although this will change with more/less heat addition at the exchanger - working perfectly in this case to compare with T1. Unlike Pressure plots, the Temperature delta differs from the 'Cooler' tests: The positive delta of the 'Heater' test is +9°C rather than -3°C. This increase validates the notion that internal friction and heat addition from the exchanger causes temperature increases to the internal air stream.

Both Pressure and Temperature are far from isentropic conditions as a heater, giving large ability to improve with better thermal insulation and increased speeds.

### 1.3.2. Tech summary (with oil):

a) Operating Speed: 800-900rpm
b) Temperature Delta: 9°C
c) BIVR: 1.464
d) Pressure ratio: 1.21-1.26
e) Pressure Stabilisation at 40 revs
f) Polytropic Index: 1.133

## 1.4. Conclusion

Despite being crudely fashioned the tests have validated with no degree of uncertainty the proof of concept, whereby a single FeTu unit with a built-in volumetric offset can create a pressure and temperature differential within a discreet (volumetrically locked) domain. The tests have also validated the reliability of our analytical studies giving us freedom to explore new domains using the same mathematic analysis.

It is perceived that such a system has a wide range of potential uses as heater or chiller. Changing from Cool to Heat mode is as simple as changing the direction of the drive. Given the clear potential of this system, opportunities will be explored to develop the test environment and commercially develop the air cycle and other informed outcomes.

### 1.4.1. Additionality:

It can be assumed that the system is entirely reversible, whereby external heat addition to the exchanger would create a high pressure within the domain, of which would in turn force the rotor to involuntarily spin as each pressure domain tried to equalise. A case for this application could be using a burner in the place of the heat exchanger and being able to drive our device for energy creation – potential EV range extension application.

## 2. Closed Loop

This section details the findings when rotational power is applied to drive the unit, recording instantaneous pressure and temperature information in the two closed loop link pipes which join the two volumetric domains. A simplistic heat exchanger formed part of each link pipe, effectively creating a complete closed loop system. The closed loop system is depicted in Figure 11 below.

The derived results will again be compared to isentropic conditions where the index ‘$\gamma$’ is 1.4 (for air).

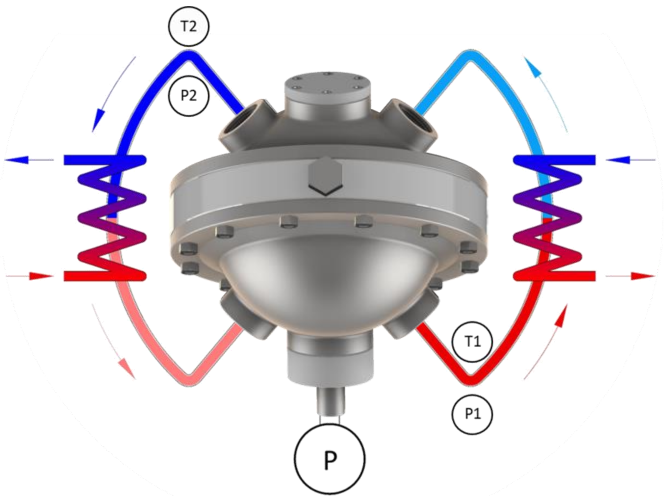


**Figure 11**: The closed loop

### 2.1. Testing Strategy

The test stand was set up on site utilising an 84mm FeTu compander with 2 x 15.7cc (non-drive side) & 2 x 23cc (drive side) chamber volumes. As with the open loop set-up, two Omega pressure transducers and two thermocouples were utilised – depicted in Figures 12 and 13, the data was logged using an Omega data recorder and a battery powered drill was used as the prime mover with a handheld tachometer recording the speed.

As pictured Figure 14, the LH exchanger carried the air moving from the 15.7cc to the 23cc chamber volume (low pass side), the RH exchanger accepting air from the 23cc chamber and delivering it to the 15.7cc chamber volume (high pass side). One complete cycle was performed every 180° of rotation. External conditions were stationary room temperature air.

**Figure 12**: Omega Pressure Transducer Probe

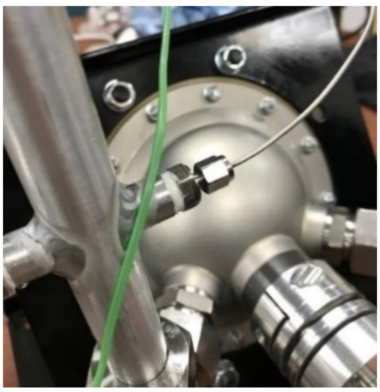

**Figure 13**: Thermocouple probe

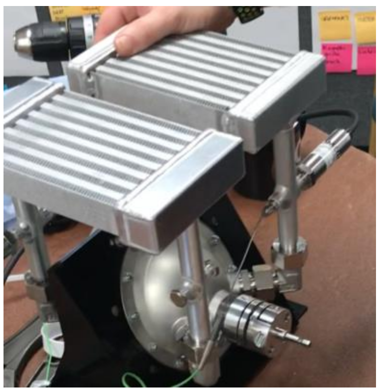

**Figure 14**: Heat Exchangers/test layout

## 2.2. Oil free (first test)

The tiny 84mm rotor exhibition unit has a relatively poor chamber volume to seal length ratio, therefore, we were unsure if the unit could perform as a 'compander' and had low expectations for the volumetric efficiency at low speed (typically 800 rpm). Such would be a lesser factor on a larger machine as the volume to seal length ratio improves ^3 as unit diameter increases.

Figures 15 and 16 plot the oil free Pressure and Temperature probe readings (as of Figure 11) and compare them to isentropic conditions when γ is 1.4.

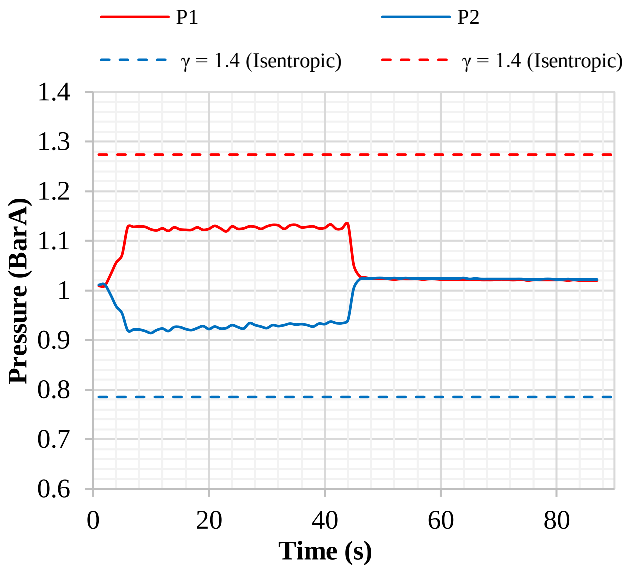


**Figure 15**: Oil free pressure performance

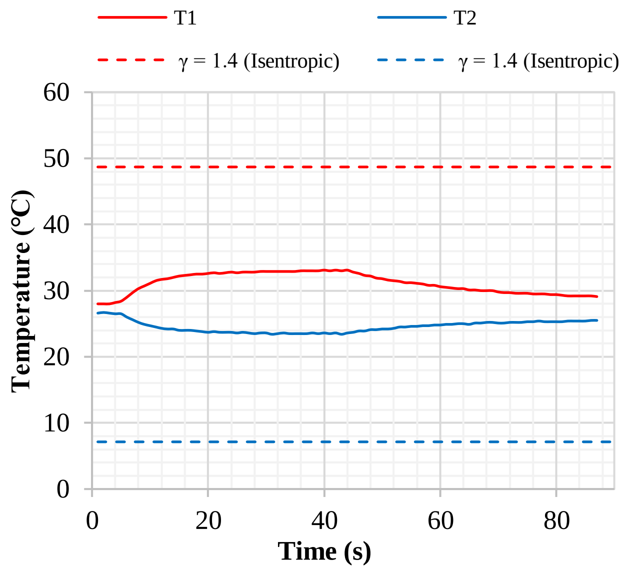


**Figure 16**: Oil free temperature performance

### 2.2.1. Observations:

Both pressure and temperature reacted immediately upon the unit being rotated; we had predicted 30 revolutions for pressure stabilisation, this was realised as factual on test. As expected, temperature was slower to trend due to the thermal inertia of the material of the machine.

Rotation (800-900 rpm) started after 2 seconds and ceased after 44 seconds. The motor was free running and did not significantly drop off in speed, indicating low friction.

A 10°C temperature delta was recorded (5°C above and 5°C below room temp) and the temperatures were still diverging after 44 seconds. In touching each exchanger, the temperature difference between them was apparent (blind tested by office individuals).

As had been envisaged both pressure and temperature reacted symmetrically about the ambient pressure and temperature in the room. As a result of the relative symmetry it was felt friction and heat generation from the machine was relatively negligible.

The upward trend on the low-pressure side of Figure 15 led to us running a static pressure test & finding and resolving a leak on the low pass side prior to running the oil flood test (Section 4).

### 2.2.2. Tech summary (without oil):

h) Running Speed: 800-900 rpm
i) Temperature Delta: 10°C (+5°C on room temp, -5°C room temp)
j) BIVR: 1.464
k) Pressure Ratio: 1.252
l) Oil free
m) Pressure Stabilisation at 30 revs
n) Volumetric Efficiency: 75% VE
o) Polytropic Index: 1.175

## 2.3. Oil Flood (second test)

At such low pressures we expected the FeTu device to have a good VE but in the absence of a flow measurement device is was difficult to determine, we therefore repeated the test after adding oil to the compressor; perceived at sufficient levels to entirely seal it.

Prior tests & analysis have shown that adding oil to the system seals it and delivers 95% VE at the pressure ranges tested. This allowed us to determine the pressure near the optimal volumetric flow point and how much of our recorded pressure readings were a function of the heat migration and how much leakage (oil eliminated leakage as a factor).

Figures 17 and 18 plot the oil flood Pressure and Temperature probe readings (as of Figure 11) and compare them to isentropic conditions when γ is 1.4.

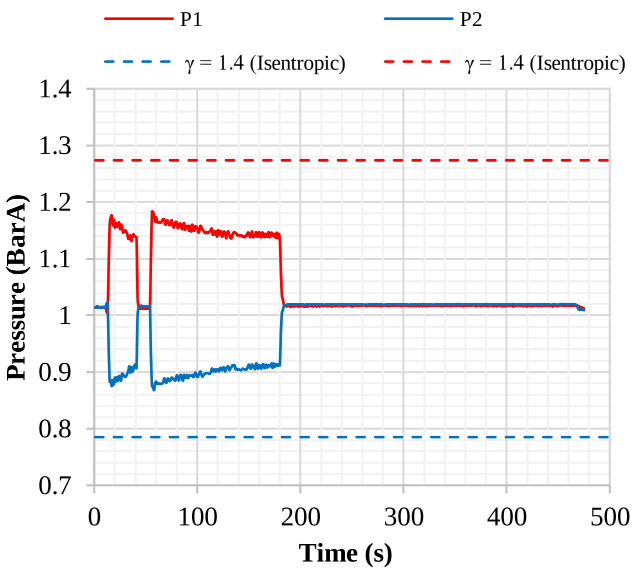


**Figure 17**: Oil flood pressure performance

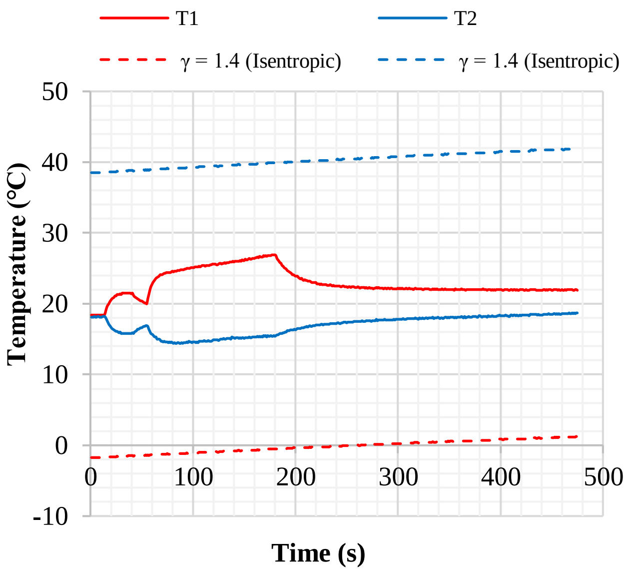


**Figure 18**: Oil flood temperature performance

### 2.3.1. Observation

We ran the test for a short burst, then changed the battery for a longer burst (@ 800 rpm). The addition of the oil increased torque (denoted by the decline of the pressure as the drill stated to slow), it also increased the friction within the machine which saw the high side migrate in temperature away from the cold side. The temperature in the room increased during the test which accounted for the general upward temperature trends.

The temperature continued to diverge despite the modest reduction in pressure as a result of the drill speed slowing. The first burst of 28 secs (timeline 13 secs to 41 secs) was with a weak battery (700rpm>400rpm). The second burst of 126 secs (timeline 54 secs to 180 secs) was with a fresh battery which ran ~800>600rpm.

This test allowed us to verify our belief that the oil free unit was running with a reasonable Volumetric Efficiency and indicated the likelihood that significant heat transfer was occurring both in the exchangers and within the compander itself. The more heat transferred the greater the deviation from the isentropic (dashed) condition.

#### 2.3.2. Tech summary (with oil):

g) Operating Speed: 800 - 400rpm
h) Temperature Delta: 12°C (+7°C on room temp, -5°C room temp)
i) BIVR: 1.464
j) Pressure ratio: 1.363
k) Oil: Liquid sealing ring (Oil – Mobil SHC Rarus 32)
l) Pressure Stabilisation at 30 revs
m) Volumetric efficiency: 95% VE (perceived)
n) Polytropic Index: 1.161

### 2.4. Conclusion

Despite being crudely fashioned the tests have validated with no degree of uncertainty the proof of concept, whereby a single FeTu unit with a built in volumetric offset can create two discreet (volumetrically locked) domains, then manage these in an equally opposed pressure domain, symmetrical and equidistant from the neutral (at rest) state. A single unit 'compander'. The tests have also validated the reliability of our analytical studies.

It is perceived that such a system has a wide range of potential uses as heat pump or chiller. Given the clear potential of this system, opportunities will be explored to develop the test environment and commercially develop the air cycle and other informed outcomes.

#### 2.4.1. Additionality:

It should be a reasonably safe assumption that the device will function in a similar manner for other working fluids, which could offer potential for an elevated cooling capacity (in comparison to ambient air).

This same logic would hold true if the system was in a pre-charged pressure condition, rather than ambient, elevating cooling capacity potential.

The system is considered entirely reversible, whereby external heat addition (to the high pass side) and heat subtraction (to the low pass side) would create & supply energy to the two pressure domains. These pressures (to an equal and combined effect) would in turn force the rotor to involuntarily spin as each pressure domain tried to equalise. In creating this flexible (constrained) domain the rotational energy afforded by the rotor could be used to drive an electrical generator.

# 3. Summary of Tests

The objective of these tests was to prove the validity of our open and closed loop air-cycle concept, this it has achieved. Given the micro scale of the test unit and the limiting conditions of the test (sample points, speeds, unquantified heat transfer), further tests will now be planned to better characterise its true performance.

The rotational speed has a direct impact on both the cooling capacity and volumetric efficiency, a sustained speed drive is on order which will allow tests at high-speed (+1,500 rpm).

The open loop test has proved capable performance as a cooler and heater with the ability to switch between cooling and heating mode by simply reversing drive direction.

The closed loop tests have proved that the FeTu device can create a high and low pressure in two locked volumetric domains. Whilst the oiled version gives an indicative pressure benchmark, it is felt a larger rotor and higher speed would bring the oil free performance closer to that of the oiled.

## 3.1. Advantages:

- Mechanical and technical simplicity
- High fault tolerance (on test the system has evidenced an ability to perform whilst leaking)
- Low system pressure, low risk
- Zero ODP, Zero GWP
- Analogue capacity control
- Low input power and negligible start up torque

# 4. Interesting 'Kissing' Phenomenon

The precise explanation of the FeTu principle is often difficult for people to assimilate but on closer examination of the pressure we can see a recognisable and repetitive trend (Figures 19 & 20), the trend is in sync with the rotation of the device and repeats every 180˚ in time with the cyclic operation of our compression chambers.

This phenomenon describes the pressure trend which one heat exchanger is subject to, in that at TDC (Top Dead Centre), when media entry and exit are isolated, there is an instantaneous agreement in the pressure readings. As we leave TDC, the symmetrical and opposed interaction of admission and exit chambers can be witnessed.

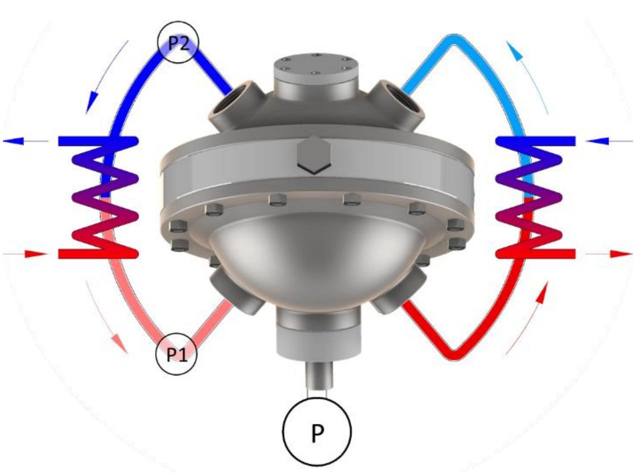


**Figure 19**: 'Kissing' Pressure Investigation – test set up

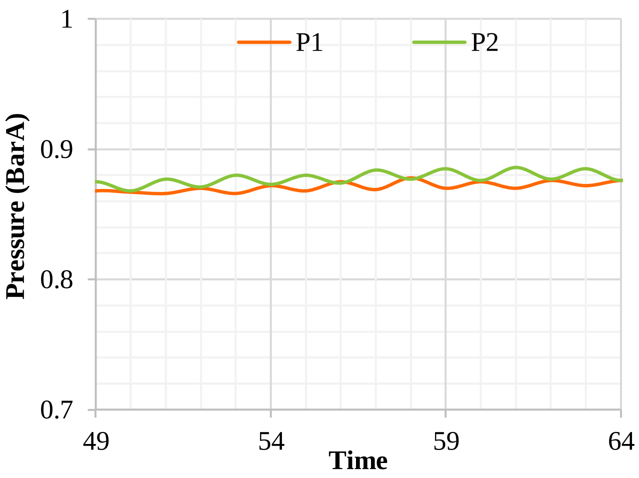


**Figure 20**: Snapshot Pressure Trace

## 5. Next Steps

In 2018 during compressor tests at the UoBath, Dr Colin Copeland analysed the test results and a polytropic index of 1.15 was calculated when the FeTu compressor is acting upon air (fully lagged). Further testing within a thermally insulated environment would allow the determination of the precise polytropic index for the unit, which would then inform the comparative performance with materials/coatings of different thermal conductivity levels. For example: The aluminium parts used had a thermal coefficient of conductivity of 180 W/m.K, the hard anodizing employed raises their emissivity (typically by a factor of 20) & raises thermal conductivity. Next tests are planned using the same base material but with a PEO (ceramic) coating which has a thermal coefficient of conductivity of 1 W/m.K, to understand how this impacts the polytropic index.

Furthermore, tests shall be run with additional pressure and temperature probes measuring at each quadrant. A high-speed drive and a torque transducer will also be utilised to fully map of the FeTu compander performance.

The tiny 84mm rotor exhibition unit has a relatively poor chamber volume to seal length ratio; therefore, we were unsure if the unit could perform as a 'compander' and had low expectations for the volumetric efficiency at low speed (typically 800 rpm). Such would be a lesser factor on a larger machine as the volume to seal length ratio improves ^3 as unit diameter increases. A larger capacity unit will also be manufactured and tested so that the cooling/heating potential can reach kW with a volumetrically efficient performance.

The closed loop tests were conducted with no pre charge pressure (atmospheric air), two analytical studies (ours & Brunel Uni) have indicated that doubling the pre charge pressure doubles the cooling/heating capacity of the same machine. Such needs to be validated on test, where a range of pre-charges could offer vast increase to performance from the same sized machine. This would overcome our early notions that air cycle coolers/heaters would be larger than normal vapour cycle machines.