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ABSTRACT

This paper is a continuing work from the same authors on the same topic of gas pulsation control using a shunt pulsation trap method by Huang (2012a, 2014). Traditionally, a serial pulsation dampener/muffler, often a reactive type, is connected AFTER the discharge of a positive displacement compressor or engine. It is capable of reducing pressure pulsation level up to 10-20 folds or 20-40 dB but is bulky and suffers sizable back pressure losses. It has been demonstrated in the previous theoretical and experimental investigations by Huang (2012a, 2014) that gas pulsations can be as effectively controlled by an alternative method, shunt pulsation trap (SPT) of a parallel configuration, which is more compact and tackles the gas pulsations BEFORE the compressor or engine discharge, hence not suffering any back pressure losses. However, it is observed that the dampening element inside SPT by a perforated plate (p-plate) induces a severe "drum effect" with enhanced vibration and noise.

This paper investigates experimentally the effect of a new dampening element inside the SPT by using circular perforated tubes (p-tubes) with minimum trap volume. It is found that p-tubes can effectively resolve the adverse "drum effect" of p-plate with improved pulsation/vibration/noise reduction. Furthermore, the use of an absorption type silencer is beneficial to further reduce noise level by 10-15 dB in addition to the p-tubes under Exhauster and Blower modes. However, this type of silencer will not have the sizable back pressure drop associated with reaction type silencers and therefore will not affect system efficiency. The integration of absorptive silencer into a p-tube based SPT would provide an optimal design choice for size/weight and pulsation/noise reduction, energy saving and for improving equipment fatigue life. The potentials for applying the SPT to screw and scroll compressors are enormous in the future since a significant portion of their operation is under off-design conditions of either an under-compression (UC) or over-compression (OC).

1. INTRODUCTION

1.1 Gas Pulsations vs. Noises (Acoustic Waves)

Gas pulsations commonly exist in HVACR, energy and automotive industry. They are believed to be a major source for system inefficiency, vibrations, noises and fatigue failures. It has been widely accepted that gas pulsations mainly take place at the discharge side of a positive displacement (PD) type compressor such as a screw, scroll or Roots as discussed in detail by Soedel's book (2007), and Mujiü *et al*. (2007), Koai and Soedel (1990), Sangfors (1999), Wu *et al*. (2004) and Gavric and Badie-Cassagnet (2000), Price and Smith (1999), Tweten *et al*. (2008) and Peters (2003). Recently by using the shock tube analogy, Huang (2012a) revealed that the nature of gas pulsations is a composition of compression waves (CW), expansion waves (EW) and an induced fluid flow (IFF). Moreover, the dynamics of gas pulsations is such that the pressure pulsations consisting of CW (coalescing into a quasi-shockwave) and EW travelling in opposite directions are the forces driving the unidirectional flow pulsation as strong pressure waves sweep across the gas at the speeds of waves.

Though pressure pulsations travel so rapidly, they can be quantitatively measured by modern high response pressure transducers and their magnitude is typically ranging from 0.002 – 2 bar (0.03 - 30 psi). By comparison, pressure fluctuations of acoustic waves are typically less than 0.0002 bar (0.003 psi) or equivalent to the pressure level of 120 dB according to Beranek (1988). Table 1 lists the corresponding magnitudes of pressure pulsations and acoustic waves in bar, psi and dB. It can be seen that the pressure level of gas pulsations is much higher and well beyond the linear pressure range of classical acoustics. That is, the “real life” pressure pulsations are non-linear waves with finite amplitude and changing wave form.

Table 1: Magnitude of acoustic waves in comparison with industrial gas pulsations (Huang, 2012a)

Acoustic Waves ⟺ Gas Pulsations							
Pressure Pulsation, bar	0.000002	0.00002	0.0002	0.002	0.02	0.2	2
Pressure Pulsation, psi	0.00003	0.0003	0.003	0.03	0.3	3	30
Sound Pres. level, L_p, dB	80	100	120	140	160	180	200

On the other hand, the frequency of gas pulsations are relatively low, ranging from 10-500 Hz while acoustic noise’s frequency typically ranges above 500 up to 10,000 Hz.

1.2 Traditional Gas Pulsation and Noise Control Methods: Reactive vs. Absorptive Silencers

Traditionally, a serial pulsation dampener, often a reactive type silencer, is connected AFTER the PD compressors for gas pulsation control as shown for a screw compressor in Figure 1.

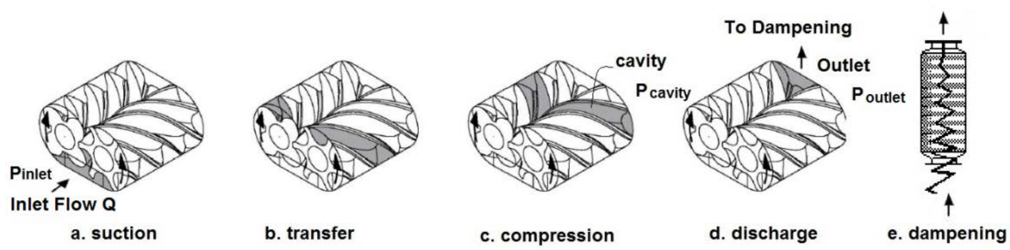


Figure 1(a-e): Traditional screw compression cycle with a serial dampener at discharge

A reactive type silencer, shown in Figure 2a, works by employing a series of chambers connected with a number of perforated tubes. Its effectiveness in pulsation control depends on the size and number of the chambers or stages of dampening. By increasing the size and number of stages attenuation is increased. An ideal design can achieve a reduction of 20 plus dB, but results in a large size which creates other problems such as inducing more noises and vibration due to the increase of surface area and supported weight. Sometimes internal dampener structure fatigue failure results in possible catastrophic damage to downstream components and equipment. Another major defect associated with a reactive type silencer is the static pressure loss that reduces the compressors overall efficiency. The pressure loss is directly proportional to the attenuation for a fixed size silencer and typically ranges from 0.4 psi up to 5 psi or even higher.

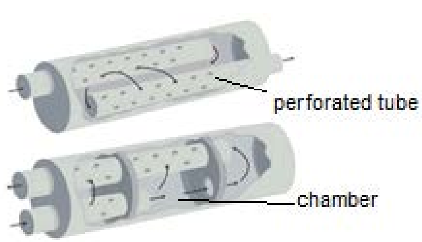


Figure 2a: Reactive silencers

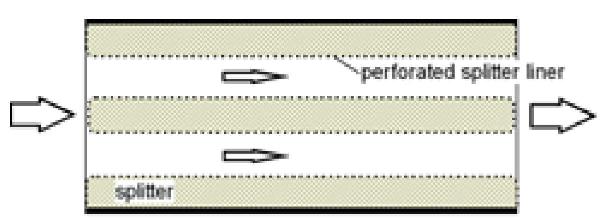


Figure 2b: Principle of an absorptive silencer

On the other hand, absorptive or dissipative silencers, shown in Figure 2b, are configured in a parallel baffle arrangement and lined with sound absorbing materials. They are commonly used in HVAC duct systems after dynamic type blowers or compressors that generate gas pulsations (acoustic waves) with smaller amplitudes and higher frequencies than PD types. They can effectively attenuate pressure fluctuations up to 20 plus dB while suffer much less pressure loss, at least an order of magnitude lower than reactive types.

1.3 Gas Pulsation Control Methods: Serial vs. Parallel (SPT) Dampening

Traditionally, serial dampening configuration of either reactive or absorptive types has been and perhaps still is the dominant method tackling gas pulsations. However, an alternative method called a shunt pulsation trap (SPT) uses a parallel configuration which tackles the gas pulsations BEFORE the compressor discharge. The SPT method is based on the shock tube theory (Huang, 2012a & 2012b) that predicts that the most dominant sources of gas pulsations are the direct results from either an Over Compression (OC) or an Under Compression (UC) suddenly discharging at the compressor outlet when running at off-design conditions.

As a brief description of the principle of a shunt pulsation trap, Figure 3 shows a Roots type blower, PD compressor at 100% UC, with a shunt pulsation trap near the compression cavity. In principle, a SPT is used to both TRAP and ATTENUATE of all three components of gas pulsation CW-IFF-EW at the same time. For comparison, a traditional discharge dampener is connected in series with the cavity, compression chamber, AFTER the discharge port, as shown in Figures 1e and 4a, and through which both the cavity flow Q and the gas pulsation flow IFF pass. While a shunt pulsation trap is connected in parallel with the cavity BEFORE the discharge port through which only the gas pulsation flow IFF passes, shown in Figure 4b. During the discharging phase of the operation, the flow cavity is pre-opened to the “trap inlet” which connects the cavity to the pulsation trap, which in turn communicates with the compressor outlet through the “trap outlet”. Between the trap inlet and trap outlet and within the shunt pulsation trap, there is a pulsation dampening means to control gas pulsations energy.

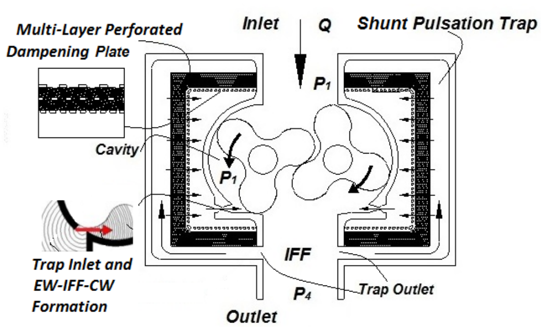


Figure 3: Roots blower with a Shunt Pulsation Trap for UC mode

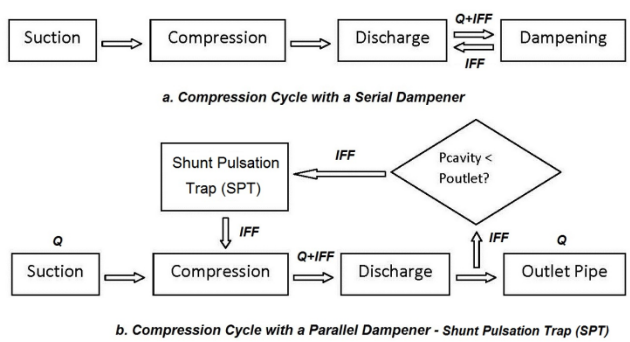


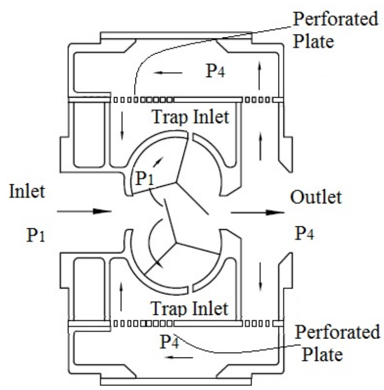
Figure 4(a-b): Comparison of a Shunt Pulsation Trap with traditional serial configuration shown for UC mode

The difference between serial and parallel configurations is fundamental and significant here as there are several distinct advantages associated with the shunt pulsation trap when compared with the traditional serially connected pulsation dampener. First of all, the attenuation of the flow pulsation IFF is separated from the main cavity gas flow Q so that an effective IFF dampening will not affect the main cavity gas flow Q, resulting in both higher system efficiency (no discharge pressure loss) and attenuation efficiency. In a traditional serially connected dampener, both the pulsating flow IFF and cavity gas flow Q travel together through the dampener where a better attenuation always comes at a cost of higher static pressure losses. So a compromise is often made in order to reduce the back pressure loss by sacrificing the degree of pulsation dampening or have to employ a very large volume and costly dampener in a serial setup. Secondly, the parallel pulsation trap attenuates the gas pulsation closer to the source of pulsation generation and in a shape more compact and conformal to the cavity shape than a serial one, resulting in smaller size and less weight.

2. EXPERIMENTAL INVESTIGATION OF SPT WITH P-PLATE AND P-TUBES

2.1 Pulsation Control Testing Using a SPT with Perforated Plate (p-plate)

To validate the shunt pulsation trap (SPT) concept experimentally, two prototypes of 75 HP and 350 HP Roots type blowers were built and tested with SPT equipped with a perforated plate (p-plate) as shown in Figure 5a (refer to Huang, 2014 for more details). The previous experimental investigations have demonstrated that a 10-fold or 20 dB pressure pulsation reduction can be as effectively achieved by the shunt pulsation trap (SPT) as a traditional reactive type silencer as shown in Figure 5b. However, SPT is much more compact in size and is not suffering any back pressure losses. The energy saving of SPT without any back pressure that compressor has to overcome with a serial silencer is significant, as shown in principle by P-V diagram in Figure 6 that was validated by tests on a 350 HP prototype with efficiency gain across the whole flow range by 5- 16% (Huang, 2014).



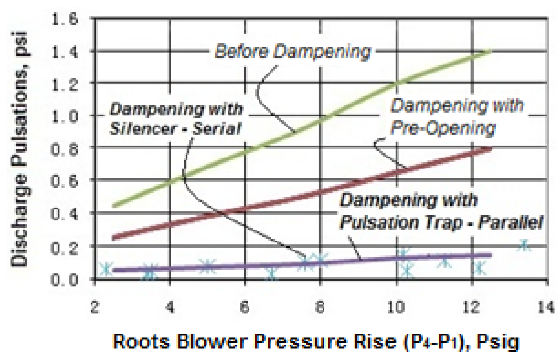
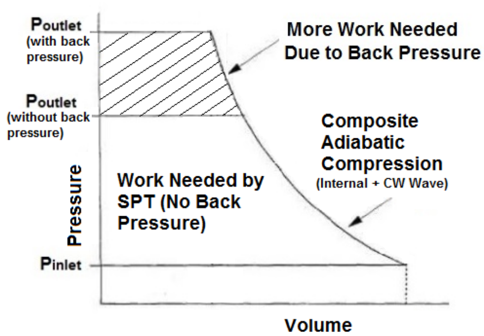


Figure 5a: SPT design with perforated plate (p-plate) **Figure 5b:** SPT test results vs. serial silencer

However, there is a downside for p-plate SPT. The most serious one is the generation of a wide spectrum of secondary vibration and noise by the dampening plate itself as they are excited by the strong EW waves and induced fluid flow (IFF) inside the shunt pulsation trap by the perforated plate (p-plate), the so called "drum effect".



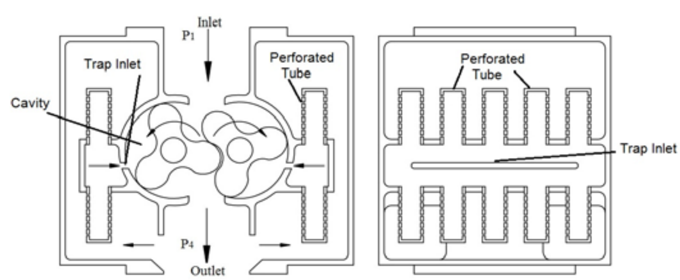


Figure 6: SPT energy saving principle on P-V **Figure 7:** SPT testing with perforated tubes (p-tube)

2.2 Pulsation Control Testing Using a SPT with Perforated Tubes (p-tubes)

To overcome the "drum effect", a new round of testing is conducted on the same 75 HP prototype as the above by using circular shaped perforated tubes (p-tubes) inside the SPT instead of perforated plate (p-plate), as shown in Figure 7. The cylindrical perforated tube offers the advantage of a balanced out aerodynamic forces induced by IFF and EW or CW waves inside a shunt pulsation trap to undergo self-cancellation thus exciting no or little secondary vibration and noise.

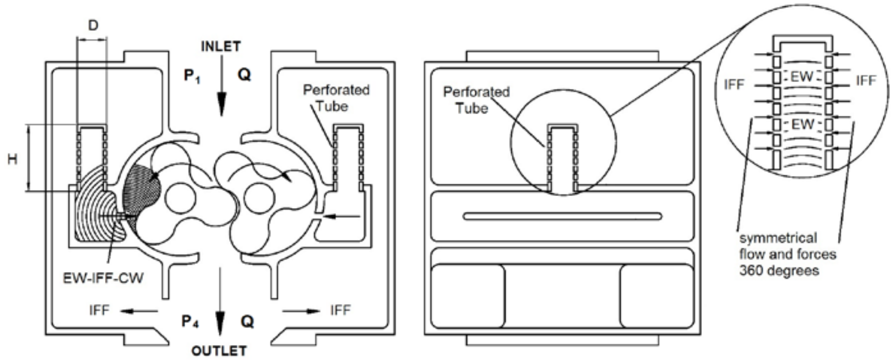


Figure 8: Working principle of perforated tube (p-tube) shown for UC mode

Pay attention to the exploded view in Figure 8 showing a SPT with at least one cylindrical shaped perforated tube (p-tube) per compressor cavity. In comparison with a SPT with perforated plate (p-plate) shown in Figure 5a, the induced flow IFF by EW waves through the holes of the p-tube are now symmetrical and the induced forces that excite the secondary vibration and noise are hence cancelled out throughout the entire perforated surface. Moreover, the perforated tube is of the cylindrical shape with a length (H) to diameter (D) ratio at least larger than 2 to 1 so that the total cylindrical surface area is much larger than the flat top end area that acts like a drum, hence eliminating so called “drum effect”.

Figure 9: Comparison of prototype setup of perforated tubes (p-tubes) with a perforated plate (p-plate)

To experimentally compare the performance of a p-tube with p-plate, new p-tube tests are conducted with the same test setup and instruments as p-plate tested before, shown in Figure 9, following ASME PTC-9 specification and pressure pulsations are measured using the same piezoelectric high response dynamic pressure transducers at the same inlet and discharge locations as before. The measured pulsation results are summarized in Figure 10 comparing various designs of p-tubes with p-plate while measured total noise level is shown in Figure 11. It is found that p-tubes can effectively resolve the “drum effect” of p-plate and improve pulsation, vibration and noise reduction.

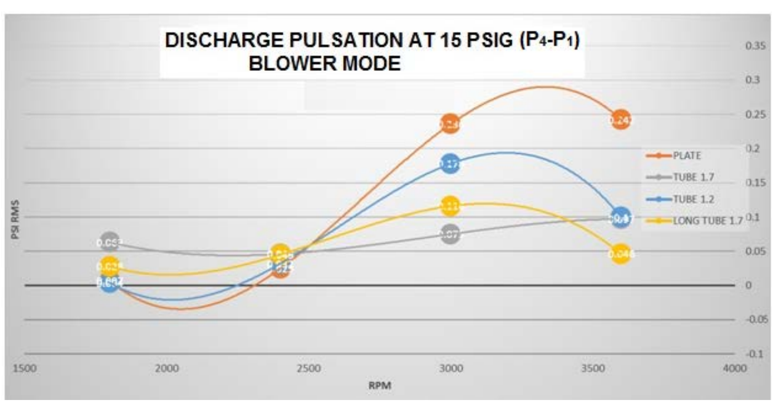


Figure 10: Comparison of measured pulsations of perforated tubes (p-tubes) with a perforated plate (p-plate)

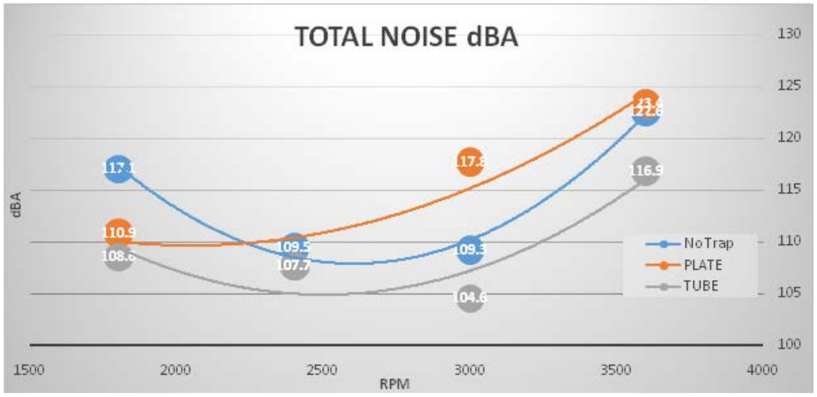


Figure 11: Comparison of measured noises of perforated tubes (p-tubes) with a perforated plate (p-plate)

2.3 Further Noise Control Testing Using an Absorptive Silencer

During previous discussed testing in section 2.2, it is observed that even with very low discharge pulse levels using SPT with p-tubes, around 0.05 - 0.2 psi as shown in Figure 10, there still appears to be a lot of noise coming from the discharge. There could be explained by Table 1 that indicates 0.03 - 0.3 psi pressure pulsations is corresponding to 140-160 dB in acoustic noise. In another words, SPT is effective with a 10-fold large pulsation reduction, say from psi to sub-psi level, the problem remains as how to further reduce the sub-psi level smaller pulsations, hence the induced noise and vibrations?

The upper limit of the maximum pulsation reduction by a SPT for Roots type is discussed by Huang (2015) in the previous theoretical and experimental investigations that gas pulsations can be generated either by a sudden velocity change (ΔU) say from a piston or lobe movement, or by a sudden opening of a pressure difference ($\Delta p41$) such as during the discharge phase of a rotary PD compressor (screw, scroll or Roots) under UC (Under-Compression) or OC (Over-Compression) conditions. The test results confirm that the dominant source of the gas pulsations for the 100% UC case is mainly from the sudden release of a pressure difference (Δp_{41}) while the non-uniform rotor movement (ΔU) induced pulsation is about one order of magnitude lower. In another word, a different scheme is needed to tackle the sub-psi level smaller pulsations at discharge in order to further reduce noises.

A traditional absorption type silencer is used at discharge together with p-tube equipped SPT prototype. Preliminary test results show the beneficial trend to further reduce total noise level by 10-15 dB in addition to the p-tubes under Exhauster and Blower mode. However, this type of silencer will not have the back pressure drop associated with reaction type silencers and therefore will not affect system efficiency (the cost of power wasted). The integration of an absorptive silencer into a p-tube based SPT would be an optimal design choice in both pulsation and noise reduction.

3. CONCLUSIONS AND FUTURE RECOMMENDATIONS

3.1 Test Conclusions

The control of large amplitude gas pulsations and the induced NVH have been a continuing challenge for over a hundred years due to its importance to the reliability and efficiency for widely used internal combustion engines and PD type compressors. Instead of following the path of traditional serial configuration, an alternative parallel approach called SPT (shunt pulsation trap) is devised and validated by experiments in this paper and the previous one (Huang, 2014) based on a new pulsation generation theory - the shock tube mechanism. It is concluded:

1. SPT (shunt pulsation trap) concept has been experimentally validated by perforated plate (p-plate) as well as perforated tubes (p-tubes) on a 75 HP Roots blower, demonstrating that it is capable of a 10-fold plus or 20 dB plus pressure pulsation reduction, as effective as a traditional reactive type silencer. However, SPT is more compact in size and is not suffering any back pressure losses as traditional reactive silencer. The

energy saving potential of SPT by eliminating any back pressure is significant with potential efficiency gain across the whole flow range by 5- 16%;

2. SPT with p-tubes does not suffer the adverse "drum effect" and is more compact and effective than p-plate with overall improved performance of pulsation, vibration and noise reduction;
3. Furthermore, the use of an absorption type silencer is beneficial to further reduce noise level (sub-psi pressure pulsations) up to 10-15 dB in addition to the SPT with p-tubes without suffering the sizable back pressure drop associated with reaction type silencers and therefore will not affect system efficiency. The integration of absorptive silencer into a p-tube based SPT would provide an optimal design for both size/weight and pulsation/noise reduction, energy saving and for improving equipment fatigue life.

3.2 Future Recommendations

Though tests so far have only been conducted for the special case of a 100% under compression for Roots type blower, it is believed that the principle of SPT control strategy could also be applied to other types of PD compressors without automatic discharge valves such as screw and scroll types that suffer even more pulsation problems under over compression (OC) or under compression (UC) than Roots type (Soedel, 2007). The shunt pulsation trap concept (SPT) with p-plate or/and p-tubes configurations could be applied in schemes as shown in Figure 12 for example. More examples and embodiments could be found in SPT patents listed in the references of this paper.

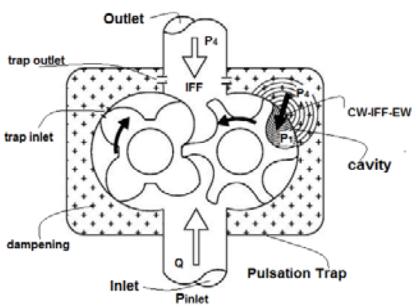


Figure 12a: Screw compressor with a Shunt Pulsation Trap for UC mode

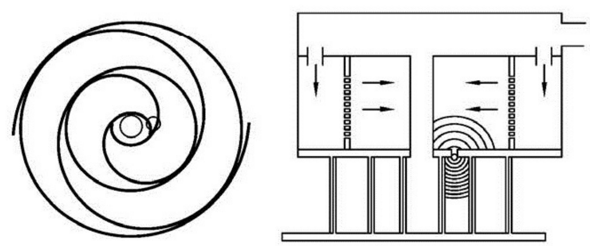


Figure 12b: Scroll compressor with a Shunt Pulsation Trap for UC mode

Finally, we hope, in our continued search to understand and control gas pulsations, more experiments based on other types of PD compressors incorporating SPT principle could be conducted under both UC and OC conditions to explore the enormous potential for this new approach. With more research and development resources devoted by both academia and industry, it is anticipated that future generation of PD compressors and Internal Combustion Engines can be designed to be even simpler in structure, smaller in size and smoother in running than those used today.

NOMENCLATURE

CW	compression wave pulsation component
EW	expansion wave pulsation component
IFF	induced fluid flow pulsation component
OC	over compression
p	gas pressure pulsation
P	absolute gas pressure
PD	positive displacement
Q	inlet volume flow rate
SPT	shunt pulsation trap
UC	under compression
ΔU	IFF velocity
V	PD compressor volume

Subscripts

1	initial low pressure in shock tube, or inlet pressure in Roots blower
2	pressure after shockwave in shock tube, pressure after CW in PD compressor
4	initial high pressure in shock tube or outlet pressure in Roots blower
Cavity	compressor cavity
Inlet	compressor inlet
Outlet	compressor outlet

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