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DEVELOPMENT AND ASSESSMENT OF A SCORE™ DEMO2.1 THERMO-ACOUSTIC ENGINE

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Abstract

The early low-cost, wood burning Thermo-Acoustic Engine (TAE) known as Demo2.0-build-1 was developed by SCORE™ at the UK Centre and was capable of achieving 22.7 Watts of electricity. This prototype was limited to an operating temperature of about 300°C and due to excessive leaks could not operate continuously above ambient pressure. To absorb a thermal heat input of 4.4 kW from the burning wood so as to fulfil the required acoustic power, the Hot Heat Exchanger (HHX) requires heating to the highest possible temperature. Therefore, a corrugated stainless steel plate HHX design that maximises heating surface area was adopted to the current Demo2 TAE design. In addition, the system is often pressurised to achieve higher acoustic intensity. Rigorous sealing of the system at high temperature is also required. A Demo2.1 TAE design based on the Demo2 TAE design and its prototype which is developed recently by the SCORE™ Centre in Malaysia was successfully constructed and well integrated with the stove. During the early construction and assembly process, fabrication difficulties and serious leak problems around the HHX's edges were found when the apparatus operated at high temperatures. This is because the uneven geometrical HHX (convolution profile) makes it difficult and relatively costly to be sealed. The Demo2.1 TAE is focused on the sealing efficiency and effective manufacturing cost by meantime to allow further modification variation. The design was made to adopt the local manufacturing technologies and materials available or easy to access in Malaysia. It also aims to minimise the parasitic heat losses to lower the system onset temperature. By removing the Linear Alternator and Tuning Volume from the system, preliminary measurements shown that the apparatus was oscillating at the frequency of 70 Hz. A much lower onset temperature was observed at around 144°C for the new configuration when the apparatus was oscillating at approximately 200 Pa. This paper describes the main design features of the Demo2.1 TAE including easy fabrication and assembly methodology, together with apparatus construction and rig test assessment.

Keywords: Design features, Oscillating, Stove, Thermo-acoustic.

Abbreviations

AHX	Ambient heat exchanger
HHX	Hot heat exchanger
LA	Linear alternator
TA	Thermoacoustics
TAE	Thermoacoustics engine
TBT	Thermal buffer tube

1. Introduction

SCORE™ is an international collaboration research project which aims to improve the life quality of over 1.5 billion people worldwide who still use biomass as their primary form of energy in household cooking and too remote to benefit from grid electrical supply [1, 2]. The objective of this project is to design and build a low-cost, high efficiency woodstove that uses about half the amount of wood of an open wood fire, creates little smoke and uses the waste heat of the Stove to power a Thermo-Acoustic generator to produce electricity for uses such as LED lighting, charging mobile phones or to charge a 12 V battery [3, 4].

Over the past few years, SCORE™ has produced a number of working prototypes to demonstrate the Thermo-Acoustic (TA) principle [5]. On the recent developments, a wood burning twin Regenerators Thermo-Acoustic Engine (TAE) design known as Demo2 TAE design was successfully developed by the SCORE™ and Aster Thermoakoestische Systemen of the Netherlands [6]. This design has evolved through five stages of development with considerable technical challenges both in the TA and manufacturing methods. The BS 7000 design process and TRIZ methodology were employed during the design phases ensuring the system functionality of each module and the fulfilment of the desired cost target.

More recently, a simplified prototype of the design known as Demo2.0-build-1 was built to validate the design principle and was tested to produce 22.7 Watts of electricity. The construction of the prototype and its testing results were described elsewhere [7]. There were few simplifications with this prototype limiting its working performance such as use of poor sealing materials and lower grade heating materials. One of the main changes was that the corrugated Hot Heat Exchanger (HHX) was replaced by two aluminium-finned heat sinks mounted back to back acting as the HHX transferring heat from the Stove to the Regenerator. However, to achieve a higher heat input from wood combustion, the HHX need to be heated up to the highest possible temperature. The corrugated HHX which has large heating surface area was adopted on the Demo2 TAE design. In addition to that, to achieve the required acoustic power, the system is often pressurised to obtain a higher acoustic intensity. Therefore, rigorous sealing of the system at high temperature is always required. During the early construction and assembly process, the Demo2 TAE design was found to be difficult to manufacture locally as the assembly process required plenty more welding assembly than expected due to the excessive leaks around the HHX's edges and misalignment assembly. This is because the uneven geometrical HHX profile makes it difficult and relatively costly to be sealed especially at high temperatures.

The Demo 2.1 TAE being undertaken at the SCORE™ Centre in Malaysia based on the early Demo2 TAE design is made to adopt the manufacturing technologies and materials available or easy to access locally. The design is focused on improving the sealing efficiency and minimising the manufacturing cost by meantime to allow further modification variation. This design also aims to minimise the parasitic heat losses to lower the onset temperature. The interface between the TAE and the Stove was redesigned and the heat leakage losses were minimised. The main components of the system such as HHX, Ambient Heat Exchanger (AHX) and Regenerator are compressed between two housings known as Upper Housing and Lower Housing, the AHX was modified to improve the sealing efficiency, the flow passage was streamlined to minimise losses and the whole integrity was designed for easy assembly and maintenance. An inexpensive method of using a composite of ceramic, (Sodium Silicate with fibre glass) and silicone sealing is used as a primary sealing and insulation material for the HHX. A volume between the Linear Alternator (LA) and the AHX known as Tuning Volume is added in this design for acoustic impedance investigation. The Thermal Buffer Tube (TBT) is made to minimise parasitic heat losses and easy fabrication. This paper will describe the main design features of the Demo2.1 TAE including easy fabrication and assembly methodology, together with apparatus construction and rig test assessment.

2. Design and Design Features

The SCORE™ TAE system is constructed from two identical engine stages (Demo2.1 TAE) positioned close together. Typically, a single-stage Demo2.1 TAE consists of five modules: HHX (corrugated Stainless steel plate), Regenerator (Stainless steel mesh), AHX (modified radiator), TBT and feedback piping (PVC pipe) [3]. Generally a LA (loudspeaker) is positioned close to one of the engine's radiator in a closed loop system [8]. The general cross-section layout of a single-stage Demo2.1 TAE with the LA attached is illustrated in Fig. 1 (Feedback piping loop not shown).

In the Demo2.1 TAE design, the main components of the system such as HHX, AHX and Regenerator are compressed by two housings known as Upper Housing and Lower Housing. The Upper Housing is made of 3 mm thick mild steel as it does not need to undergo high working temperatures and cost less than Stainless steel. The TBT and Stubflange are integrated to the Upper Housing. The Lower Housing is made of 3 mm thick Stainless steel due to its low heat conductivity property so to minimise the parasitic heat loss as it is directly in contact with the HHX. This also requires less welding work and less difficult to assembly as well as enable future maintenance.

A volume of 260×250×10 mm between the LA and the AHX know as Tuning volume is allocated in the Demo2.1 TAE design as shown on Fig. 1. This volume is made to be adjustable for acoustic impedance matching investigation by adding or removing materials as it is part of the uncertain parameters to be identified in this design.

To achieve adequate electrical output, early tests have shown that a higher acoustic intensity is required and so the working pressure is now increased from 100 k to 200 kPa gauge. The entire loop needs to be perfectly sealed under the pressure of at least 200 kPa gauge [9]. One of the challenges of the Demo2.1

TAE design is to seal the corrugated Stainless steel HHX with the Lower Housing. The uneven surface/convolutions profile and working requirements of the HHX makes it difficult to be sealed perfectly and relatively costly. The sealing have to withstand high temperature (>500^{o}C) and high pressure (>200 kPa gauge) when the apparatus operated at high temperatures. The UK Centre has proposed an effective solution to physically eliminate the HHX's convolutions profile by using Waterjet cutting technology to cut a convolutions solid bar to fix with the HHXs' convolutions thus providing a flat surface to give easy way of sealing. In the Demo2.1 TAE, an inexpensive method of using a composite of ceramic with RTV silicon is proposed. The composite of ceramic is a mixture of liquid Sodium Silicate and fibre glass material. This is used as a primary sealant and insulation to prevent heat transferring to the HHX edges as both materials has a high melting point but low heat conductivity. The profile of the ceramic was streamlined on the inner ends to reduce loss of the flow passage as shown on Fig. 2 while the outer ends are flatten to provide a flat surface for sealing when the ceramic is solidified. The RTV silicon is then applied to all edges of the HHX and it is placed into the Lower Housing.

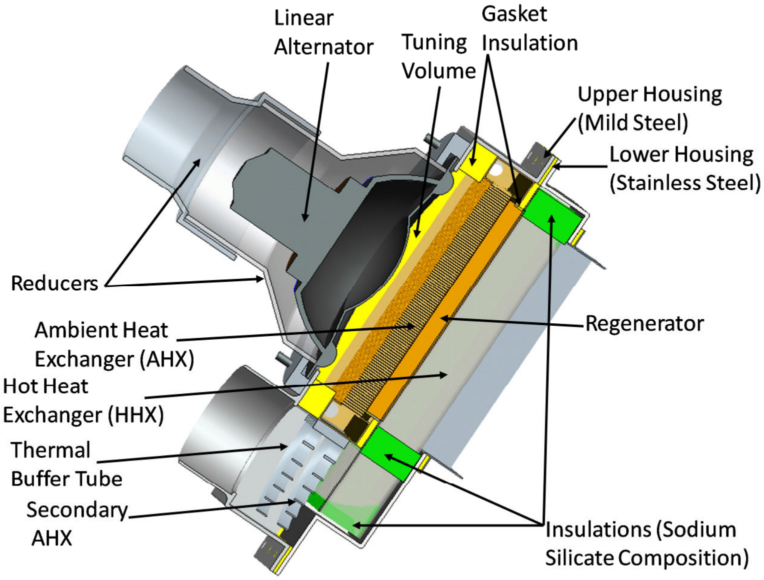

Fig. 1. Cross Section Layout of a Single-Stage Demo2.1 TAE Design in Malaysia.

In the early Demo2.0-build-1 TAE test, the TBT volume was found overheating due to the high parasitic heat of gas from the convolutions that was not dissipated properly. To avoid heat accumulation in the TBT or to dissipate heat more efficiently, the TBT volume for the Demo2.1 TAE design was made directly in contact with the AHX without partitions. The advantage of eliminating the partition and integrating the TBT volume with the Upper Housing as described is to allow the hot gas to be directly cooled by the AHX immediately when it leaves from the convolutions so as to enhance the heat transfer efficiency.

Other than this, an aluminium heat sink works as a secondary AHX is attached on the lower end of the radiator to absorb the heat from the gas effectively as shown on Fig. 2. Besides, it also works as a flow straightener to avoid flow streaming.

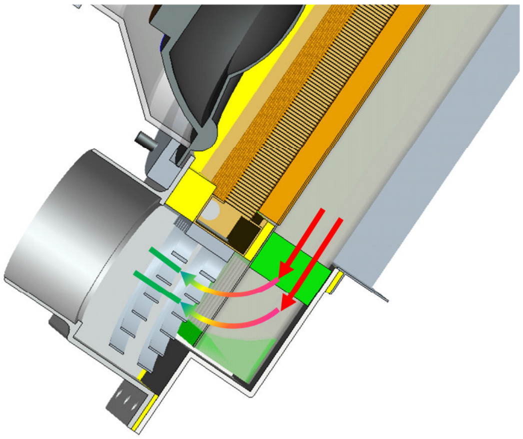

Fig. 2. Gas Oscillating Path Curve between the Convolutions and TBT Volume is Cooled by the Aluminium Secondary AHX. The Flow is also Straightened by the Secondary AHX to Avoid Flow Streaming.

3. Apparatus Construction

As described previously, the main objectives of the Demo2.1 TAE design are effective sealing, low manufacturing cost, easy to assemble and able to be modified for tuning purposes and different configurations. The entire fabrication process is made to adopt the local manufacturing technologies and materials available or easy to access in Malaysia.

The Upper Housing is manufactured by stamping a 3 mm thick mild steel plate to the required depth, and then the edges of the stamp area are welded together. This will reduce the amount of welding needed and possible leakage areas. A diameter of 150 mm (6 inch) and a diameter of 75 mm (3 inch) holes are drilled with a boring tool on the frontal plate of the housing. Six M8 threaded shafts are welded around the 150 mm hole for the LA to be attached. This also allows the LA to be easily removed and replaced by a stubflange with a 2 mm thick mild steel hollow cylinder for the feedback pipes to be attached. The same size of another hollow cylinder is welded aligned to the 75 mm hole for the feedback pipes to be attached as well. An adaptor with an inner thread of M10x1.0 is welded to the housing to allow the Pressure Transducer to be attached. A hole is drilled on each sides of the housing to be aligned and attached with the AHX's fitting for water intake and outlet. A volume between the LA and AHX know as Tuning Volume is added to smoothen the flow transition from the engine to the feedback pipes. This volume is adjustable by inserting or removing aluminium plates with a 90 mm diameter hole aligned to the feedback pipes. A modified car radiator functioning as AHX is then placed after the aluminium plates and the water intake and outlet holes are aligned and then screwed through the holes on the sides of the housing using the fittings. In fact, a gasket with a rectangular hole is placed between the aluminium plates and the radiator to accommodate the radiator surface roughness due to manufacturing tolerance.

Similar to the Upper Housing, the Lower Housing is also manufactured by stamping and welding. The material used is 3 mm thick Stainless Steel. The size of the housing made is based on the size of the corrugated HHX available. The corrugated HHX is then placed into the housing and its edges are sealed as discussed in the previous section. A 200 mm by 200 mm hole is cut for the heat supply. This housing is then aligned and clamped with the Upper Housing and then the holes are drilled through both housings' flanges with well alignment to allow them to be fastened together by M8 bolts. This makes the engine to be disassembled easily for maintenance or investigation of the inner parts such as change the size of the Tuning Volume. A high temperature resistant gasket is placed between the housings for better fastening force and reducing the heat conduction path from the Lower Housing to the Upper Housing.

Between the corrugated HHX and AHX is the Regenerator, made by stacking 30 pieces, 80-mesh Stainless Steel wire mesh machined to a square size of 200 mm by 200 mm. The diameter of the mesh wire is 162 μm and pitch of the wires is 315 μm. Its volume porosity ϕ is calculated to be about 96% and the hydraulic radius r_h is about 97 μm. The hydraulic radius is smaller than the air's thermal penetration depth $\delta\kappa$, which is around 280 through the Regenerator [9]. The randomly stacked meshes are then compressed by the corrugated HHX. The edges of the Regenerator are insulated with low heat conductivity fibre insulation. When assembled, the AHX will press the Regenerator against the corrugated HHX to keep it in place. Additionally, two K-type thermocouples were inserted from the top side of the Upper housing and the sensing heads were placed on both sides at the centre of the Regenerator to monitor the AHX and HHX's temperature.

Lastly, the system is connected by the 5-mm thick U-PVC pipes with inner diameter of 80 mm and fittings. The pipes are cut to length to approach a quarter wave travelling loop. Silicone grease is applied on each fitting for sealing. A standard size pressurisation valve was mounted on the pipe to allow the system to be pressurised.

4. Assessment and Discussion

The TAE system is a closed loop including two identical Demo2.1 TAEs positioned close to each other in what we call a dual Regenerator configuration, a LA generator developed by SCORE™ is placed on one of the TAE to convert acoustics energy into electricity power and the entire system is connected by low cost U-PVC pipes so called feedback piping loop [6]. The lengths of each loop are configured to approach a ¼ wavelength and ¾ wavelength as quarter wave devices are able to reduce reflections [10]. The system is hence integrated with the high efficiency stove casted by concrete and the general outline of the testing setup is illustrated on Fig. 3.

The test was conducted at atmospheric pressure and the ambient temperature was about 28.7°C. A total amount of 2.5 kg wood of approximately 15% moisture content was consumed over the first 90 minutes. The Stove produced an average flame temperature of around 750°C and a maximum of about 1000°C. The HHXs' temperature increased rapidly as shown on Fig. 4 from 50°C to 350°C in about 10 minutes after the ignition was started. The inconsistent temperatures profile on both HHX1 and HHX2 may be due to the uneven heating supply on the convolutions. The rejected heat temperature difference of about 1.5°C (water intake and outlet's temperature difference) was observed at water flow rate of 3.8 Litter/minute. The amount of heat loss from the rejected heat is approximately 400 W. The water on the pans without covers (about 1.5 Litters each, total 3 Litters) were boiled in almost 1 hour after the ignition.

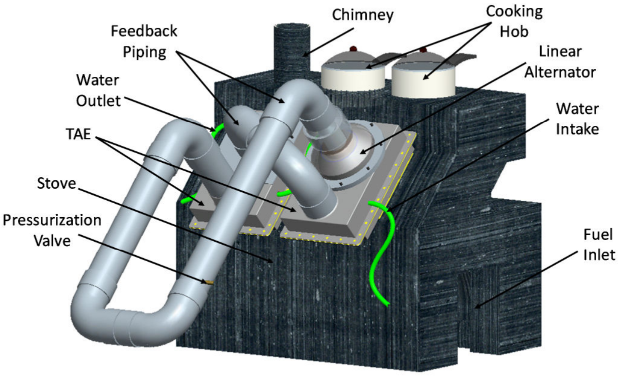

Fig. 3. General Outlet of the Testing Setup Powered by Wood Combustion.

An additional of 2.5 kg wood was refilled at about 100 minutes after the ignition. Both of the HHXs' temperatures started rising up significantly again and one of the HHX's temperatures reached the highest temperature of 460°C as shown on Fig. 4. Simulation results and past experiences show that the temperature difference was high enough to drive the system oscillating under the right conditions. Various types of boosting methods such as system pressurised were performed to get the oscillation during the testing process.

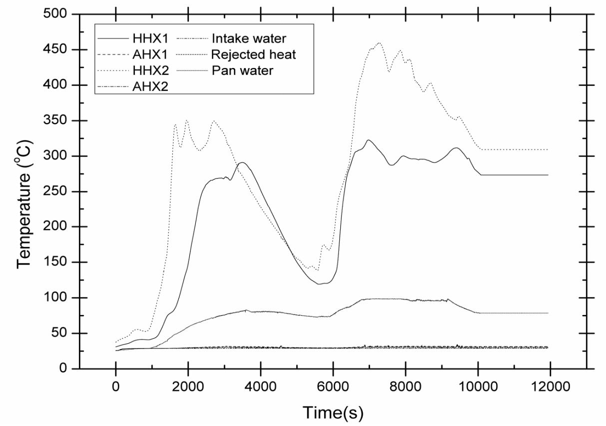

Fig. 4. Temperatures vs. Time during the Testing Period.

Consequently, several analogies such as Volume Analysis were performed to get the apparatus oscillating. A graph of cross section area versus position relative to the LA's diaphragm was plotted as shown on Fig. 5 to identify the position of any parasitic volume regions in the closed loop. The height of any rectangular cross section and the diameter of the circular cross sections are plotted as well to better illustrate the shape of that region (i.e. different rectangles can produce same cross section area). The volume of each section of the loop can be obtained simply by integrating the area under the curve from point to point.

The regenerator is estimated to have 96% porosity. The volume taken by the Radiator fins are not included for simplicity. Both the TAEs' dimensions are taken as identical as the differences from manufacturing tolerances are negligible.

The graph plotted clearly illustrates the parasitic volumes in the system. It is believed that adding the Tuning Volume at the existing feedback piping (un-optimised condition) configuration could shift down the gain optimum. Simulations show that the existing feedback piping configuration will force the engine to oscillate at the possible frequency however it is required very high Regenerator temperature difference. It was proposed that reducing the length of the ¼ wavelength loop to raise the loop gain at the oscillating frequency could slightly lower the onset temperature or increases the pressure amplitude. However, the physical dimension of the ¼ wavelength loop is difficult to change due to the design geometric. Lowering the oscillation frequency by increasing the length of the ¾ wavelength loop at which frequency gain and reflection are optimal is adopted to complement the loop gain.

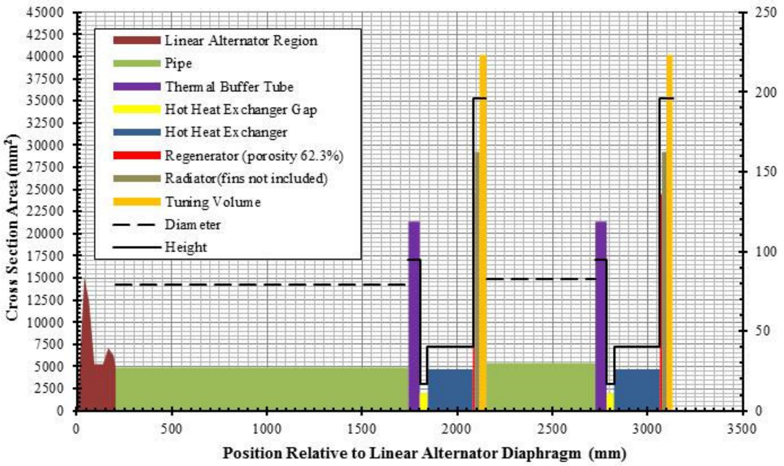

Fig. 5. Graph of Cross Section Area vs. Position Relative to Linear Alternator Diaphragm.

To approach the oscillation and then optimise the operating frequency, the LA is removed temporary from the system and the Tuning Volume is filled with materials. The length of the ¾ wavelength loop was increased in steps of 200 mm to observe the actual optimum gain of the system. In addition to that, a 2 kW electrical heater is used as heating power instead of wood combustion. The new general outline of the testing system is illustrated in Fig. 6.

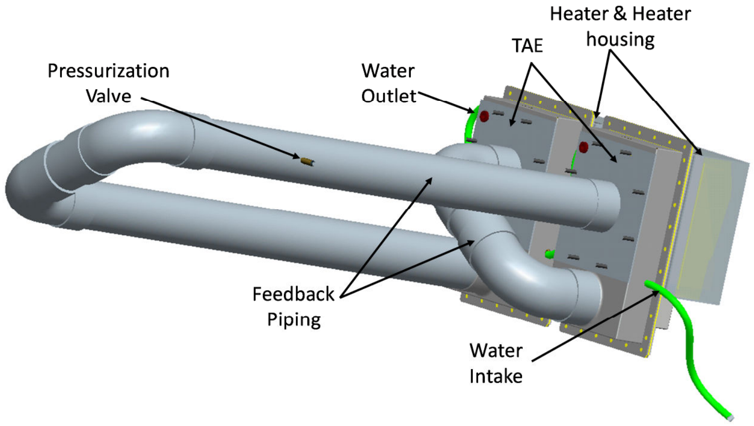

Fig. 6. General Outlet of the Testing Setup Powered by Electrical Heater.

The apparatus was orientated 45 degree upwards as same as when it is installed on the Stove. The heater power was measured to be approximately 1KW each and 2 KW in total. The water flow rate of the AHX was set to be about 3.8 L/min. The length of the ¼ wavelength was fixed at 570 mm whereas the ¾ wavelength was varied from 2800 mm to 3800 mm for loop gain optimum observation. The experiment was carried out under atmospheric pressure and the ambient temperature was about 27°C. The initial length of the ¾ wavelength was 3800 mm and was reduced in steps of 200 mm until 2800 mm. In Fig. 6, the TAE with the water outlet is called Stage 1 whereas the one with the water inlet is called Stage 2 in this paper. The initial oscillating peak pressure of the apparatus are summarised and shown on the Table 1.

Table 1. Experimental Results when the Apparatus Oscillating at Initial Condition.

3/4 wavelength (mm)	Stage 1		Stage 2		Peak Pressure (Pa)		Frequency (Hz)
	AHX * (°C)	HHX * (°C)	AHX * (°C)	HHX* (°C)	P_1	P_2	
3800	31	422	30	409	1316	1143	63
3600	32	429	30	432	1316	1076	65
3400	32	420	30	454	1271	1237	70
3200	32	418	30	482	1189	1214	74
3000	32	390	31	509	1051	1221	77
2800	32	409	30	515	861	1217	81

* The AHX and HHXs' temperatures are not the onset temperatures. They were recorded at the peak pressures stated (P_1 and P_2).

Oscillation occurred through the length of the ¾ wavelength loop varied from 2800 mm to 3800 mm. A very low onset temperature was observed at around 144^{o}C when the engine oscillated at approximately 200 Pa. Obviously, the performance of this apparatus was found to be relatively stable when it was operating at the frequency of 70 Hz where the length of the ¾ wavelength loop was about 3.4 m long. At this length configuration, the pressure of each stage of the apparatus was found to be the closest to each other among the entire testing lengths. As the lengths increase or decrease, the peak pressure of each stage tends to be unstable and slowly floating away.

5. Conclusions

The main design features of the SCORE™ Demo2.1 TAE was described including performance optimisation and cost effectiveness in manufacturing methods as well as easy assembly and having flexibility for further medication variation. The apparatus construction accommodated with rig test assessment was performed.

Apparently, the preliminary measurements of the Demo2.1 TAE with the Stove are shown which demonstrate that the Stove is able to produce and transfer sufficient heat to the TAE. The Volume Analysis along the entire loop of the apparatus was illustrated in a figure. Increasing the length of the ¾ wavelength and removing the LA from the system enhanced the oscillation to occur. A very low onset temperature was observed at around 144^{o}C when the apparatus was oscillating at approximately 200 Pa. Finally, the apparatus was working stably at the frequency of 70 Hz. The peak pressure of about 1271 Pa was found at the initial condition.

The proposed inexpensive method of using a composite of ceramic as a primary sealant and insulation for the corrugated HHX is working perfectly.

Acknowledgement

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