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# DESIGN OF TWO-STAGE THERMOACOUSTIC STIRLING ENGINE COUPLED WITH PUSH-PULL LINEAR ALTERNATOR FOR WASTE HEAT RECOVERY

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## ABSTRACT

Thermoacoustics is suitable technology for recovering waste heat and generating electricity. In this paper, a novel thermoacoustic electricity generator using a push-pull linear alternator is proposed. It is aimed to recover part of the internal combustion engine exhaust waste heat and produce useful electricity. It consists of two half wave length identical stages and a linear alternator connected in between them. The physically identical stages produce identical wave halves with acoustic pressure out of phase. The availability of two points having the same pressure amplitude out of phase provides the opportunity to connect the linear alternator to two points in each stage to run the alternator in a "push and pull" mode. The proposed engine is able to produce more than 138.4W of electricity at thermal-to-electrical efficiency of 25.1% equivalent to a fraction of Carnot efficiency of 45.1% while using helium pressurized at 40 bar.

## 1. INTRODUCTION

Day by day, power demand rises all over the world. In the last decades, a lot of environmental impacts have been found and proven as caused by the power generation technologies. This creates a thinking approach towards clean and environmentally friendly technologies. Thermoacoustic power generation technology could be considered as one of such technologies.

The working principle of thermoacoustic devices is based on a thermoacoustic effect which enables producing sound waves from thermal energy, or vice-versa. Thermoacoustic devices are generally described as acoustic resonators filled with a gas as a working fluid and containing a porous medium (regenerator) with heat source and heat sink (heat exchangers) adjacent to it. The gas inside the resonance tube (within the porous medium limits) will undergo a thermodynamic cycle somewhat similar to the Stirling cycle. In thermoacoustic engine, the working gas absorbs heat from high temperature side of the porous medium and rejects heat to the low temperature side while producing work in the form of sound oscillations as an output.

Looped tube thermoacoustic engine is one of the simplest traveling wave configurations and consists of long resonator (one or more wave lengths) which contains the regenerator unit and the Linear Alternator. Investigations of a looped tube thermoacoustic system have been done by Sakamoto et al. (2006, 2012). These investigations have been done on a combined thermoacoustic engine and refrigerator. Using air as a working gas, the system gave a cooling power at cooling efficiency of about 0.15 W and 0.13%, respectively. They subsequently improved performance to reach 0.8 W of cooling power and 1.5% of cooling efficiency, by using a mixture of helium and argon (50:50) instead of air.

The looped engine configuration has also been used in SCORE project. Thermoacoustic engine was found to be able to convert waste heat from the cooking stove to electricity. The engine has been made of commercially available materials and air at atmospheric pressure has been used as working fluid (Yu et al., 2012). The simulated efficiencies of thermal to acoustic, acoustic to electric and thermal to electric conversion were 4.6%, 53% and 2.4%, respectively producing electricity of 8 W. Abdoulla et al. (2013) subsequently improved the performance of this engine by adding a resonance tube as a branch to connect the alternator to the loop. The efficiencies have been improved to be 23%, 59.7% and 3.5% (thermal to acoustic, acoustic to electricity, and thermal to electricity, respectively). The generated electricity has been increased to reach 13 W.

Abduljalil et al. (2009) constructed a looped tube TA engine that has a ceramic regenerator with fine square channels instead of the conventional stainless steel mesh core. The maximum measured acoustic power was about 26 W. Abduljalil et al. (2009) continued their work with some improvements and the acoustic power reached 34 W.

The multi-stage thermoacoustic engines were proposed to produce more power whenever there is enough supply of heat to be used. It was also found that the multi-stage TA engines are a solution to provide a low onset temperature (Chen, 2012). Multi-stage engines have been pioneered by de Blok (2010, 2012). Basically, they have low acoustic loss because of lower acoustic dissipation in the resonance and feedback loop. The identical multiple stages have been presented as feasible from the construction point of view because of having identical components per stage. The name "self-matching" indicates that each stage has an independent power extractor. From the losses point of view, it is better to design a self-matching engine in order to avoid high power spots and minimize losses. Four novel TA four-stage engines have been presented by de Blok (2010). All the engines have four power extraction points with productivity ranging from several watts to 1.64 kW at heat to electricity efficiency no more than 8.2%.

Some efforts towards a two-stage engine with one linear alternator have been undertaken as an outgrowth of SCORE project. Abdoulla et al. (2012) used DeltaEC to numerically design a two stage TA engine working as an electricity generator. The model gave encouraging results of 6% thermal to electricity efficiency and generating 130 W of electric power. Chen et al. (2012) built two engines: one driven by propane burner and the other by wood burner. The propane driven TA engine generated 15 W of electricity and the wood burner one produced 22.7 W. Both have used a low efficiency alternator. Kang et al. (2015) experimentally generated 204 W using a two-stage thermoacoustic looped engine with two loudspeakers. The engine found to be able to run with thermal to electric efficiency up to 3.43%.

This paper presents a design model of a waste-heat driven thermoacoustic electricity generator in terms of system design, parts specifications and predicted performance. The engine model has been done using DeltaEC modelling tool. The thermoacoustic engine designed has two stages with a Linear Alternator connected in between at two points having equal but out of phase acoustic pressure amplitudes. The connection of Linear Alternator in this configuration allows it to be run by the effect of acoustic pressure on both sides and work in a"push-pull" mode.

## 2. SYSTEM CONFIGURATION

The current system is a one wave length thermoacoustic engine. The configuration consists of two identical stages each having power extraction point. The two power extraction points help to avoid high power spots and allow the stages to act as self-matching. The self-matching stages have the same identical acoustic pressure and volume flow rate amplitudes but which are out of phase. It means that each of two identical points on the two stages have the same acoustic pressure and volumetric flow velocity amplitude but shifted 180º in phase. This configuration allows connecting the linear alternator to two points having the same amplitudes acting out of phase. This connection increases the system efficiency by increasing the power output and decreases the acoustic losses.

This enhancement could be interpreted using the power generation formula. The amount of acoustic power generated or dissipated by the linear alternator is directly proportional to the acoustic pressure amplitude $|p_1|$, volumetric flow velocity $|U_1|$, and the phase angle between them $\Phi_{pU}$.

$$E = \frac{1}{2}\,|p_1||U_1|\cos\Phi_{pU}$$

where E is the acoustic power and $|p_1|$ is the acoustic pressure difference on the sides of the linear alternator. The method of linear alternator connected to two points having out of phase amplitudes will increase the acoustic pressure difference on the sides of the linear alternator and hence enhance the performance of the engine.

## 3. MODELLING

To verify the idea explained in the previous section, a model has been done constructed using DeltaEC. The DeltaEC shooting method showed that it was unable to run two identical stages as expected. The two identical stages when each has a power extraction point should have the same thermal and acoustical performance and this is what the shooting method failed to follow. The modelling has been done as half of the engine which is one stage and the other stage has been represented as a self-excited flow at the other side of the linear alternator.

Each thermoacoustic engine stage consists of a thermoacoustic core followed by a branch to the linear alternator and finally there is a long feedback tube. The total length of the engine is one wave length and each stage is exactly half wave length as shown in Fig.1.

**Figure 1** Illustration of the thermoacoustic engine.

The engine loop is 16 m long and uses helium at 40 bar as working gas. The thermoacoustic core consists of ambient heat exchangers AHX, regenerator, hot heat exchanger HHX, thermal buffer tube TBT and the second ambient heat exchanger 2$^{nd}$AHX. The core has a diameter of 10 cm, reduced to 7.5 cm at the end of the TBT and the 2$^{nd}$AXH. The core layout is shown in Fig. 2. The core is arranged vertically; the AHX at the top and the 2$^{nd}$AHX at the bottom. This has been experimentally verified to enhance the temperature distribution in the regenerator and the TBT and reduce the onset temperature (Liu et. al. 2002, Abduljalil et. al. 2009).

The heat exchangers used in the model are parallel plate heat exchangers having a plate spacing of 1 mm and 65% blockage ratio. The proposed heat exchangers of this project are all to be fabricated using wire cutting. The wire cutting is to form tiny channels through a block of metal to form cross-flow heat exchangers. The channels are 1 mm wide leaving 0.5 mm fins in between, as shown in Fig. 3. In the experimental work to follow the hot air will be used to simulate the exhaust gases to maintain helium at the HHX side at 400ºC and the water will be used as the cooling liquid at the AHX and 2$^{nd}$AHX to maintain helium at 25ºC.

The AHX is of 30 mm length and fabricated out of Copper. It is placed at the top of the thermoacoustic core. It consists of seven channels on the helium side and eight on the cooling water side. The regenerator is located below the AHX. It consists of 75 mm thick stack of woven wire stainless steel screen punched holder with a diameter of 101mm. The diameter of the screen wire is 71μm. The calculated volume porosity and hydraulic radius are 75.85% and 57.5μm respectively. The HHX is to be fabricated out of low carbon steel. It is 40 mm long and follows the regenerator. It has nine channels on the helium side and ten channels on the hot air side.

The HHX has two collars having inner and outer diameter identical to 4" pipe of schedule 40. These collars are to prevent damaging the tiny channel from damaging by the welding heat as it will be welded to a pipe and reducers as shown in Fig. 2. The thermal buffer tube TBT located between the HHX and the $2^{nd}$AHX consists of three parts: 4" diameter pipe, 4"-3" reducer, and 3" diameter pipe. The two pipes are 30 mm long. The reducer of the TBT will help to supress the Rayleigh streaming. The $2^{nd}$AHX is similar in shape and material to the AHX but it is 20 mm long and 3" diameter. It has five channels on the helium side and six channels on the cooling water side.

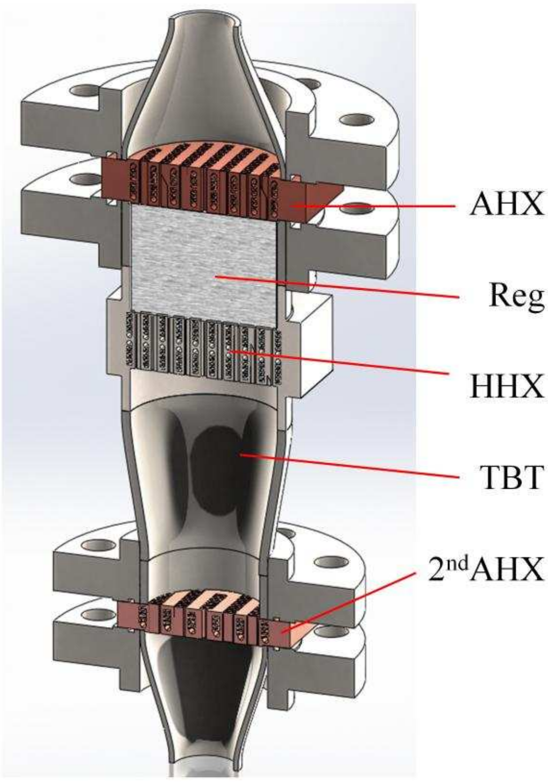
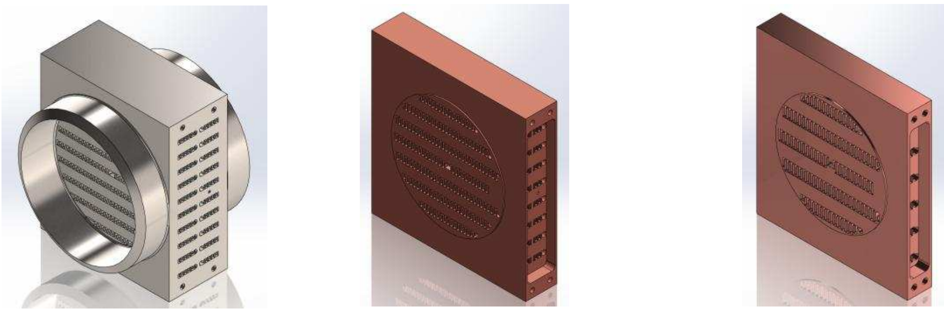



**Figure 2** Cross-section of the thermoacoustic core



HHX AHX 2ndAHX

**Figure 3** Heat exchangers

There is a 100 mm long pipe connecting the AHX to the T-branch. The T-branch is leading to a branch and a trunk. The branch is the link between the loop and the linear alternator. The trunk is 7.3 m long feedback loop. The feedback loop consists of 7.05 m long pipe having a diameter of 1.5” and 0.25 m long pipe having a diameter of 1”.

The linear alternator should have two pistons to be convenient to be used in this system. The two pistons will be accommodated at the end of the branch of each loop. One will be subjected to positive acoustic pressure and the other to negative acoustic pressure at the same time. The positive pressure produces a push to the piston while the negative pressure produces a pull both to the same direction and hence the combined effect is a push-pull.

Two different linear alternators are proposed to be used in this experiment. A Q-Drive linear alternator (Model 1S132M) and one fabricated by a partner at the University of Manchester. These two alternators both have one piston only. A design model has been made in a way that the engine will be able to run any of these linear alternators efficiently. First the Q-Drive linear alternator will be used to test the thermoacoustic engine till the amendment of the adding a second piston to the locally fabricated one completed.

## 4. NUMERICAL RESULTS

The DeltaEC run results of a configuration explained above for both linear alternators will be presented in this section. The results of the Q-Drive linear alternators will be presented and the results of the locally manufactured linear alternator will be given in the summary by the end of this section.

The numerical results showed that the engine runs at a frequency of 56Hz. The engine was found to be able to produce 138.4 W of electricity through the linear alternator out of 551.2 W of heat. The heat is injected to the system through the HHXs of the two stages at a value of 275.6W at each stage. The thermoacoustic engine efficiency is determined as the output represented by electricity gain over the input represented by the heat transferred to the engine. The engine efficiency is 25.1%. This efficiency could be considered as the raw efficiency and divided by the Carnot efficiency to obtain the relative Carnot efficiency. The Carnot efficiency could be calculated using temperatures around the regenerators which are the temperatures of AHX and HHX. The relative Carnot efficiency of the current system is 45.1%.

Each stage produces an acoustic power of 113.4 W, and thus the engine produces 226.8W of acoustic power. The acoustic efficiency is defined as the acoustic power generated to the heat transferred to the engine. The acoustic efficiency of the engine is 41.6%. The other important efficiency to mention is the linear alternator efficiency. The linear alternator efficiency is the ratio to the electricity produced to the acoustic power consumed by the linear alternator. The linear alternator in this configuration producing 138.4W of electricity out of 172.5W of acoustic power fed through both sides of it (86.2 W each side). The linear alternator efficiency is 80.2%. Fig.4 shows the acoustic power distribution along the engine. It shows that 76% of the generated acoustic power is consumed by the linear alternator and 15.1% is dissipated in the feedback loop.

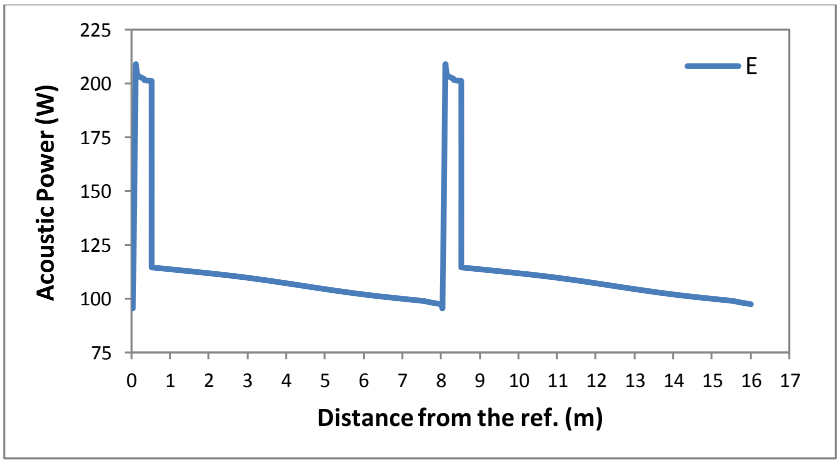



**Figure 4** The distribution of acoustic power along the loop, the reference is the HHX of the first loop

The acoustic pressure and volumetric flow rate around the engine is shown in Fig.5. It shows that the choice of the position of the regenerator is correct (at 0.03 and 8.3m). This position is at the acoustic pressure anti-node and volumetric velocity node to maintain high acoustic impedance in the regenerator and hence small acoustic loss due to velocity.

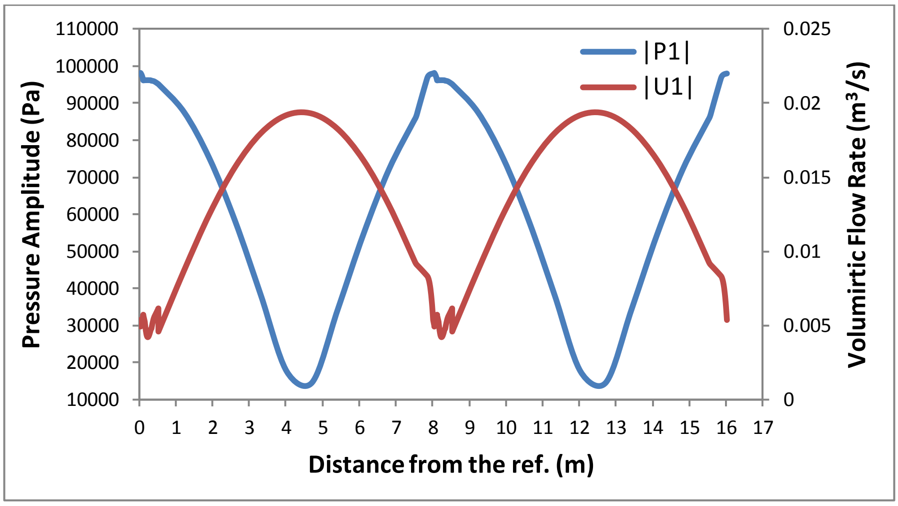



**Figure 5** The distribution of acoustic pressure and volumetric flow rate along the loop, the reference is the HHX of the first loop

The equation of the acoustic power generated or dissipated by the linear alternator explained before is the same equation of acoustic power flowing in the x direction in any segment. The preferred phase angle between the phases of acoustic pressure and volume flow rate is near the traveling wave phasing which is zero. This is very important to be achieved especially in the regenerator because it produces more acoustic power at this phasing. In the looped type thermoacoustic engine, there is no control on the phasing. In the current configuration it is about 53.8° in the middle of the regenerator. Fig.6 shows the phase difference along the engine. It shows that the phasing is near to the standing wave phasing in the feedback pipes.

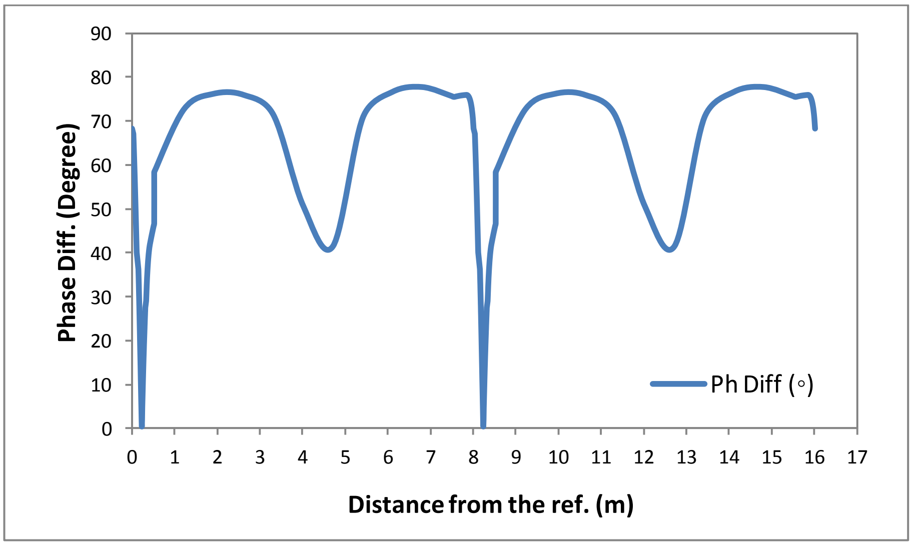



**Figure 6** The phase difference in the loop, the reference is the HHX of the first loop

A compact thermoacoustic engine configuration has been examined to set a correct phasing inside the regenerator and to reduce the length of the engine. The compact design was based on increasing the thermoacoustic core cross section and replacing the feedback pipes with small diameter pipe to act like acoustic inertace and a large diameter pipe (larger than the thermoacoustic core diameter) to act like compliance. This configuration found able to set a traveling phasing in the regenerator and reduce the engine length to 8.5m. However it was found that the total power flow starts to flow in reverse and most of the heat transferred to the system through the HHX is rejected by the 2$^{nd}$AHX. This limits the performance of the thermoacoustic engine at the heat to electricity efficiency of no more than 9.5%.

The theoretical results of the fabricated linear alternator are lower than these of the Q-Drive. The main reasons of lower performance is that the Q-Drive linear alternator has lower mechanical resistance and better electricity conversion characteristics. All the results are summarized in Table 1.

**Table 1** Thermoacoustic simulated results using the fabricated and the Q-Drive linear alternators

| Parameter | Fabricated Linear Alternator | Q-Drive Linear Alternator |
|---|---|---|
| Generated Electricity | 119.6W | 138.4W |
| Heat/electrical efficiency | 20.7% | 25.1% |
| Heat/acoustic efficiency | 43.9% | 41.2% |
| Linear alternator efficiency | 66.7% | 80.2% |
| Fraction to Carnot efficiency | 37.1% | 45.1% |

## 5. CONCLUSION

This work introduces a novel two-stage thermoacoustic engine generating electricity by running a push-pull linear alternator. Compared to the traditional traveling wave thermoacoustic engines, it potentially has advantages of generating power from two points on the loop to reduce the power losses and increase the generated electricity. A numerical simulation has been performed to obtain the optimum design for the engine. The distribution of acoustic power, pressure amplitude, volumetric flow rate and phase difference have been presented to understand the characteristics of the system. The results showed that it is able to generate 138.4 W of electricity at a heat to electricity efficiency of 25.1 out of a temperature difference of 375ºC of the hot and cold sides of the regenerator.

## REFERENCES

Abdoulla, K., Yu, Z. & Jaworski, A.J., 2012. Design of a Low-Cost Two-Stage Thermoacoustic Electricity Generator For Rural Communities In Developing Countries. In ICSV19. pp. 1–8.
Abdoulla, K., Kang, H. & Jaworski, A.J., 2013. Travelling wave thermoacoustic electricity generator for rural areas using a side-branch alternator arrangement. In World Conference of Engineering.
Abduljalil, A.S., Yu, Z. & Jaworski, A.J., 2009. Construction and Performance Characterization of the Looped-Tube Travelling-Wave Thermoacoustic Engine with Ceramic Regenerator. International Journal of Engineering and Applied Sciences, 5:3, pp.139–143.
de Blok, C.M., 2010. Novel 4-Stage Traveling Wave Thermoacoustic Power Generator. In ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels. pp. 1–8.
de Blok, C.M., 2012. Multi-Stage Traveling Wave Thermoacoustics In Practice. In ICSV19. pp. 1–8.
Ceperley, P.H., 1979. A pistonlessStirling engine-The traveling wave heat engine. J. Acoustical Soc. Am., 66,1508-1513.
Chen, B., 2012. Development and Assessment of Thermoacoustic Generators Operating by Waste Heat from Cooking Stove. Engineering, 04(12), pp.894– 902.
H. Liu, E. Luo, H. Ling, J. Wu . (2002). The Influence of Thermal Natural Convection on a Traveling-Wave Thermoacoustic Engine. Cryocoolers . 12 (2), 447-450.
Huifang Kang, Peng Cheng, Zhibin Yu and Hongfie Zheng, (2015). A two stage traveling-wave thermoacoustic electric generator with loudspeakers as alternators. Applied Energy 137 (2015) 9-17.
Sakamoto, S. & Watanabe, Y., 2006. Experimental study on resonance frequency of loop-tube-type thermoacoustic cooling system. Acoustical Science and Technology, 27(6), pp.361–365.

Sakamoto, S., Sahashi, K. & Watanabe, Y., 2012. Improving Thermoacoustic System Efficiency, Measurement of a Sound Field in the Phase Adjuster. Proceedings of Symposium on Ultrasonic Electronics, 33, pp.215–216.
Swift, G., 2001. Thermoacoustic: a unifying perspective for some engines and refrigerators Fifth draf., Los Almos National Laboratory.
Yu, Z. & Jaworski, A.J., 2012. Demonstrator of a combustion driven thermoacoustic electricity generator for remote and rural areas of developing countries. In ICSV19. pp. 1–8.