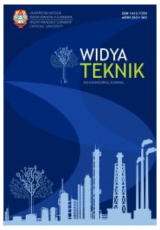
Widya Teknik
Volume 23 No. 3, 2024
Journal homepage: http://journal.wima.ac.id/index.php/teknik/index



Article

Simulation of the effect of regenerator porosity on the performance of zero centigrade thermoacoustic cooler generated by the single-stage thermoacoustic machine for sustainable refrigeration

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Abstract: Refrigeration systems are an essential need in everyday life. There are lots of modern industry that uses refrigerator for helps maintain temperature stability from overheating and prevents the product from drying out protected from dirt and insect attacks. However, the refrigeration system used in industry still uses a refrigeration system vapor compression and using chlorofluorocarbon (CFC) refrigerant and hydro-chlorofluorocarbons (HCFCs) which are harmful to the environment. Therefore, it requires thermoacoustic cooling generated by the engine single-stage thermoacoustic. This research was conducted numerically. In this research, the effects are simulated stack porosity on the performance of thermoacoustic cooling generated by a single-stage thermoacoustic machine at 0°C. the porosity was varied from 0.37 to 0.97. It was found that the stack porosity was optimal when the porosity is 0.97 and the performance of the cooler is 52 %. Moreover, the lowest heating temperature for the thermoacoustic machine is 217°C. This temperature can be used for waste heat recovery.

Keywords: porosity; thermoacoustic; cooler; machine; sustainable refrigeration.

1. Introduction

Air conditioning and refrigeration systems are an essential part in everyday life. Nowadays, many modern industries use refrigeration machines (refrigerator) to maintain temperature stability from overheating and prevent the product from being attacked by dirt or insects. However, refrigeration systems used in industry uses a vapor compression refrigeration system with refrigerant chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) which are harmful to the ozone layer and increase the Global warming potential (GWP). Based on Presidential Regulation of the Republic of Indonesia RI No. 71 of 2011 concerning implementation of National Greenhouse Gas, CFC and HCFC produces exhaust gas that can

Received 13 November 2024; Accepted 5 December 2024, Published 5 December 2024
ISSN 1412-7350 / © 2024 by the authors

damages the ozone layer and has global warming potential (President of the Republic of Indonesia, 2011). GWP caused by CFC and HCFC gas is much greater than C02. One kilogram of CFC and HCFC gas is released into the air will cause a global warming effect equivalent to 4,800 kg of gas C02 (Isnanda, 2019). As consequence, the temperature is increasing and has a negative impact on life.

Indonesia has the largest power generation company which utilizes geothermal heat as its energy source Generating electricity is often referred to as a geothermal power plant. To produce large electrical power, it uses geothermal heat with a high temperature of >225°C and the temperature of 150°C - 225°C, while the temperature less than 225°C is not used (Utami, 2019). It becomes waste heat if it is untreated and will damage the environment and have a negative impact on the environment.

On the other hand, Indonesia has been facing the energy crisis and therefore, the Government through PP No.79 of 2014 concerning The National Energy Policy has regulated it to overcome energy crisis problems. The target for the new and renewable and sustainable energy in 2025 are at least 23% and 31% in 2050 (President of the Republic of Indonesia, 2014). Therefore, there is a need for new technological breakthroughs that can be utilized and convert waste heat into new energy that can drive cooling machines effectively and environmentally friendly. This thermoacoustic cooler will become a new technology by utilizing waste heat becomes the energy source where is the cooling system used is to absorb heat or pump heat from low temperature to high temperature.

Thermoacoustic is a branch of science that deals with conversion acoustic energy (sound energy) and thermal energy (heat energy) (Farikhah and Ueda, 2017). The results of this energy conversion will give rise to several interesting phenomena such as self-sustaining gas oscillations and heat pumping effect. To produce a thermoacoustic effect, namely the engine (prime mover) and thermoacoustic cooler (cooler) which are often used also called a heat pump (heat pump) (G.W Swift, 1988).

In general, thermoacoustic coolers are driven by acoustic power which is driven by a thermoacoustic engine (prime over). In the field of thermoacoustics, there are two types of heat driven cooler; thermoacoustic cooler driven by a single stage engine (Yazaki, et al, 2002) and cooler driven by a multi-stage engine (De Blok, 2012)

Some researchers have been attracted to coolers driven by multi-stage engines due to the ability to reach initial temperatures in the engine is lower than a single-stage engine. However, the low temperature causes decreasing acoustic power, so that the temperature pumping is small (Zang, 2016). Additionally, multi-stage machines require a lot regenerator in thermoacoustic machine to process high acoustic power. However, this configuration appears to be more complicated than a single-stage engine.

In thermoacoustic machine, regenerators are the most important parameter. It converts thermal energy into acoustic energy. There is an important parameter of the regenerator, namely porosity. Porosity is also called as blockage ratio, which is a fraction of the cross-sectional area of the total narrow tube to the total plates area of the regenerator machine.

Setiawan (Setiawan, 2013) investigated how the porosity of the regenerator affected to a decrease in thermoacoustic refrigerator temperature. Stack porosity is determined by the thickness and distance between the plates. This research using a porosity variation of 0.5 – 0.85, with a plate distance of 0.5 mm to 1.5 mm and plate thicknesses of 0.3 mm, 0.4 mm and 0.5 mm. The measurement was carried out with two resonators with a length of 0.8 m and 1.0 m with air pressure of 1 atmosphere and room temperature. It was found that there was optimum porosity that provides the greatest temperature reduction, and there is the tendency for optimum porosity to shift to larger values and the temperature drop becomes greater when using piles with thinner plate. On the other hand, this study reveals information that more useful than the porosity of the stack itself. This research, found that a stack with thinner plates tends to provide a decrease temperature.

Farikhah and Ueda (Farikhah and Ueda, 2017) conducted research numerically on the influence of porosity regenerator on thermoacoustic cooling performance for extremely cooling temperature. This research uses a circular tube and traveling waves. To obtain optimal porosity values from the engine regenerator and cooling regenerator. This research uses variations in porosity regenerator 0.77 – 2. The working gas uses helium (He) under pressure 3.0 MPa. The ambient temperature and cooling temperature are set at temperature 28°C and -32°C, while the heating temperature of the machine is determined as a result of calculations. It was found that the optimal porosity is 1.1. However, this for -32 C cooling temperature.

There are a few researchers who investigated the effect porosity on the performance of thermoacoustic coolers. Based on the issues, it is important on selecting optimal porosity to obtain optimal cooling performance especially for zero centigrade of cooling temperature. Therefore, it is essential to find the effect of porosity on the performance of zero centigrade thermoacoustic cooler generated by the single-stage thermoacoustic machine for sustainable refrigeration. Moreover, Finding the optimum porosity is important to guide the engineers to construct an efficient thermoacoustic engine.

2. Materials and method

2.1. Models

Thermoacoustic cooler models in a single-stage thermoacoustic machine shown in Figure 1. It consists of two regenerators; One in the machines and one in the cooler. Type of tube used is a loop tube to execute the travelling wave. The position of the machine regenerator between the ambient heat exchanger and hot heat exchanger, while the cooler stack position is between the ambient heat exchanger and cold heat exchanger.

The length of loop tube is 2.8 meters and its cross-sectional radius is 20 mm. The length of the machine and cooler regenerator have the same value, 40 mm. The narrow radius of the machine and cooler regenerator is 0.1 mm and 0.5 mm, respectively.

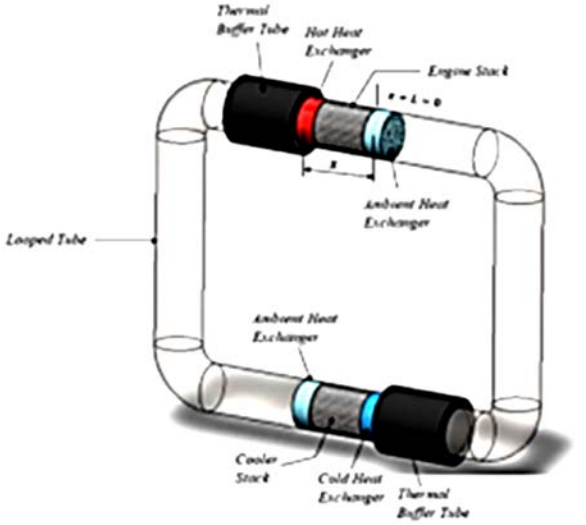

Figure 1. Thermoacoustic Cooler

The working gas is Helium at 3 MPa. The cooling temperature is set at 0 ℃ and the ambient temperature is 28 ℃ . The porosity of the regenerators is the parameter that will be varied. Hence, the optimal performance will be achieved.

2.2. Numerical Calculation

In calculating the transfer matrix, two equations were used. The equation derived by Rott (Rott,1969). The equation momentum and continuity in a flow pipe are written following eq. (1) and (2), respectively (G. W Swift, 2017).

$$\frac{dP}{dx} = -\frac{i\omega\rho_m}{A(1-\chi_v)}U \tag{1}$$

$$\frac{dU}{dx} = -\frac{i\omega A[1+(\gamma-1)\chi_\alpha]}{\gamma P_m}P + \frac{\chi_\alpha - \chi_v}{(1-\chi_v)(1-\sigma)}\frac{1}{T_m}\frac{dT_m}{dx}U \tag{2}$$

where P is the pressure wave oscillation, U is wave velocity, ωis the angular frequency of the acoustic waves, ρ is the average density, A is pipe cross-sectional area, γ is the ratio of specific heat, T_m is average gas temperature, P_m is the average pressure, and σ is Prandtl's number. Thermoacoustic function, which shows the geometry of the device were denoted as χ_α and χ_v .

2.3. Calculation of Performance of the thermoacoustic cooler

The Performance of the zero centigrade thermoacoustic cooler generated by the single-stage thermoacoustic machine. This refrigerator is set for cooling temperature at 0 ℃ . The performance of the cooler can be calculated following eqs. (3) to (7).

$$\eta_e = \frac{\Delta\dot{W}_h}{\dot{Q}_h} \tag{3}$$

$$\eta_{2,e} = \frac{\eta_e}{[(T_h - T_a)/(T_h)]} \tag{4}$$

$$COP = \dot{Q}_c/\Delta\dot{W}_c \tag{5}$$

$$\eta_{2,c} = COP/[T_c/(T_a - T_c)] \tag{6}$$

$$\eta_{tube} = \Delta\dot{W}_c/\Delta\dot{W}_h \tag{7}$$

where $\Delta\dot{W}_h$, $\dot{Q}_h$, η_e are the acoustic power generated by the thermoacoustic machine, heating power, and thermal efficiency, respectively. Heating, ambient and cooling temperature are denoted as T_h , T_a , and T_c , respectively. *COP,* $\dot{Q}_c$ and $\Delta\dot{W}_c$ are coefficient of performance, cooling power and acoustic power that consumed by the cooler. η_{tube} is the efficiency of the looped tube. $\eta_{2,e}, \eta_{tube}$, and $\eta_{2,c}$ are the second law efficiency of the machine, efficiency of the tube and second law efficiency of the cooler.

3. Results and discussion

3.1. *Efficiency of thermoacoustic machine*

Figure 2 shows the exergy efficiency of the machine. As can be seen in the figure, when the porosity increases, so the exergy efficiency of the machine goes down from 62.6 % to 51.7 % and achieves the highest value as the porosity is 0.37. It indicates that when the porosity of the machine is small, the efficiency of the machine will be high.

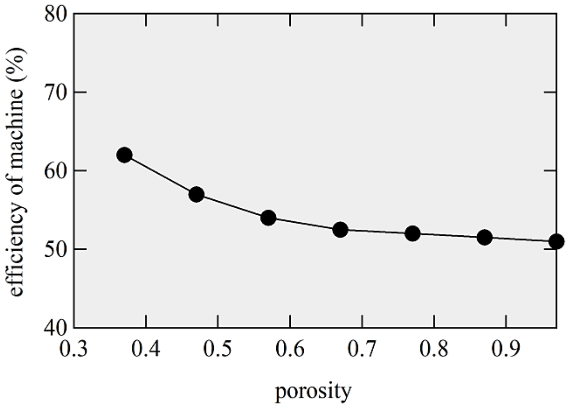

Figure 2. Efficiency Machine Vs Porosity

3.2. *Efficiency of thermoacoustic cooler*

Figure 3 shows the exergy efficiency of the cooler. As can be seen in the figure, when the porosity increases from 0.37 to 0.67, the exergy efficiency of the cooler rises from 13.4 % to 36.2 % and then the efficiency decreases from 36.2 % to 30.1 % at 0.67 to 0.97. It implies that the cooler will work at the optimum level at the optimal porosity (0.67). In other words, the porosity should not too small not too wide.

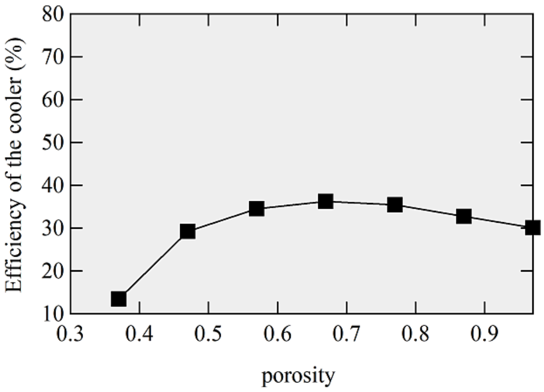

Figure 3. Efficiency of the cooler Vs Porosity

3.3. *Efficiency of loop tube*

As shown in Figure 4, efficiency of tube increases as the porosity rises. When the porosity increases from 0.37 to 0.97, the efficiency of the tube rises from 14.7 % to 26.1 %. It implies that the efficiency of the tube will improve when the porosity becomes wider. It means that the dissipation along the looped tube is small as the porosity is large.

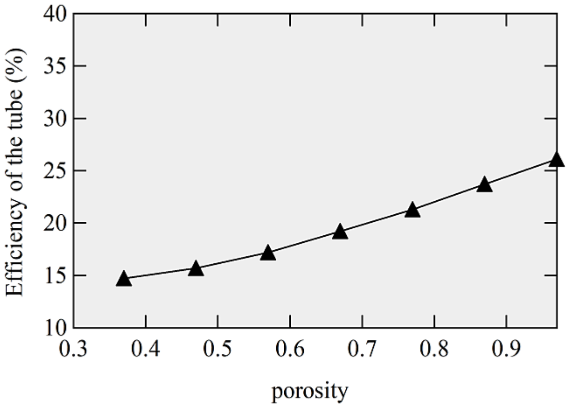

Figure 4. Efficiency of the tube Vs Porosity

3.4. *Heating temperature of the the machine*

The heating temperature can be shown as the gradient temperature (fig. 5). As can be seen in figure 5, the temperature to generate the engine improved when the porosity increases from 0.37 to 0.97. It was found that the minimum temperature is 490 K (217 ℃). It indicates that the thermoacoustic cooler could produce refrigeration at zero centigrade by utilizing low heating temperature of the machine if the porosity is large.

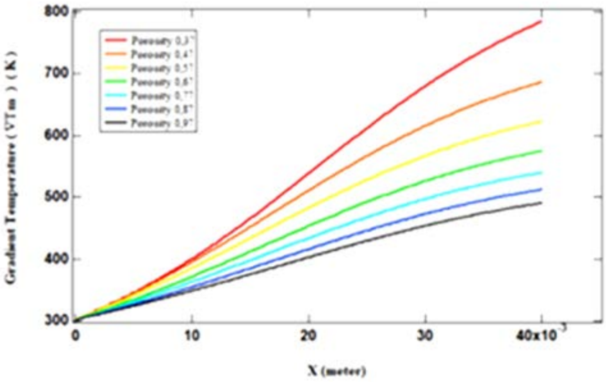

Figure 5. Gradient Temperature along the regenerator thermoacoustic machine along the tube.

4. Conclusion

The effect of regenerator porosity on the performance of the zero centigrade thermoacoustic cooler generated by thermoacoustic machine was numerically investigated. It was found that when the porosity large at 0.97 so the efficiency of the tube will high while efficiency of the cooler will high when the porosity is 0.67. However, the efficiency of the machine is low when the porosity is 0.97. In addition, the heating temperature of the thermoacoustic machine is low when the porosity is large at 0.97, which is good for waste heat recovery. Thus, the optimum porosity can guide the engineers to design an efficient thermoacoustic cooler. This is good for sustainable environment which has zero ozone depletion layer and global warming potential due to the absence of the harmful refrigerant. Moreover, the refrigeration can be generated without electricity. Therefore, it leads the high energy efficiency. Thus, we consider that this cooling technology has bright future for sustainable refrigeration.

Author contributions

Conceptualization, methodology, supervision was done by Irna Farikhah. The sofware, investigation, data analysis, and writing the original draft were conducted by Irna Farikhah and Edo Putra Aldiansyah. Resources was conducted by Setyoningsih Wibowo and Sigit Ristanto and Edo putra aldiansyah. Funding Acquisition was done by Sigit Ristanto and Nur Khoiri.

Conflict of interest

The authors declare no conflict of interest”

Acknowledgment

The investigation is supported by Institute for Research and Community Service, Universitas PGRI Semarang.

References

Presiden RI. *Peraturan Pemerintah Republik Indonesia.*, Pub. L. No. 71 (2011)

Isnanda, Y. Rosa, E. Adril, Feidihal. 2019. *Pengaruh Retrofit Refrigeran CFC-12.* https://ejournal2.pnp.ac.id/index.php/jtm/article/view/232

Utami, S. W., Farikhah, I., Khoiri, N., Patonah, S., & Kaltsum, U. (2019, November). Kajian Numerik Pengaruh Jari-Jari Stack terhadap Pemanasan Suhu Rendah Mesin Termoakustik Gelombang Berjalan. In *Prosiding Seminar Nasional Lontar Physics Forum* (pp. 23-30). https://conference.upgris.ac.id/index.php/lpf/article/view/560

Presiden RI. *Peraturan Pemerintah Republik Indonesia.*, Pub. L. No. 79 (2014).

Farikhah, Irna, & Ueda, Y. (2017). Numerical Calculation of the Performance of aThermoacoustic System with Engine and Cooler Loop s in a Looped Tube. *Applied Science Article*, *7*, 1–14. http://dx.doi.org/10.3390/app7070672

Farikhah, I., & Ueda, Y. (2017). The effect of the porosity of regenerators on the performance of a heat-driven thermoacoustic cooler. In *Proceeding of the 24th International Conference on Sound and Vibration (24 ICSV).*

Swift, G. W. (1988). Thermoacoustic Engines. Journal *of Accoustical Society of America*, *84*(4), 1145–1180. https://doi.org/10.1121/1.396617

Yazaki, T., Biwa, T., & Tominaga, A. (2002). A pistonless Stirling cooler. *Applied Physics Letters*,*80*(1). https://doi.org/10.1063/1.1431695.

Zang, X., Chang, J., Cai, S., & Hu, J. (2016). A multi-stage travelling wave thermoaccoustic engine driven refigerator and operation features for utilizing low grade energy. *Energi Conversion and Management*, *114*(224), 33. 59. http://dx.doi.org/10.1016/j.enconman.2016.02.035

Setiawan, I., Utomo, A. B. S., Katsuta, M., & Nohtomi, M. (2013). Experimental study on the influence of the porosity of parallel plate stack on the temperature decrease of a thermoacoustic refrigerator. In *Journal of Physics: Conference Series* 423 (1), 1-6. **DOI** 10.1088/1742-6596/423/1/012035

Rott, N. (1969). Damped and Thermally Driven Acoustic Oscillations in Wide and Narrow Tubes. *Z. Angew. Math. Phys.*, *20*, 230–243.

Swift, G. W. (2017). *Thermocaoustic: A Unifying Perspective for Some Engines and Refrigerators*(II). https://doi.org/10.1007/978-3-319-66933-5.