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THERMOACOUSTIC COOLING WITH NO REFRIGERANT

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ABSTRACT

The Brundtland Report (also known as Our Common Future) has placed sustainability of energy resources and environmental degradation on a common global agenda. Increasing awareness has spurred much research into alternative clean energy technologies. Thermoacoustic cooling as an environmentally friendly refrigeration system is one of the research areas being pursued. Although not commercially available, successful systems have been completed. There are, however, still many fundamental issues related to the thermoacoustic effects and the associated heat transfer that must be addressed. This paper reports a portable counter-top thermoacoustic cooling apparatus designed and fabricated at the Universiti Teknologi Malaysia (UTM). Based on a standing wave resonator tube, the system with a pvc resonator tube of 60 mm diameter which was initially at 24°C, accomplished cooling effects under a minute, up to 18.5°C, without the use of chlrofluorocarbons (CFCs) or other similar refrigerants which have been known to be hazardaous to our living environment. Another acrylic 110 mm diameter tube once recorded 8°C with the ambient held at 23°C. The cooling in the first system was repeatable but not significant enough for practical applications. However, with no refrigerants used and its relatively simple manufacturing, a thermoacoustic cooling system is a potentially clean cooling system to be further investigated for practical or specific applications.

Keywords: Clean technology; Portable; Resonator; Standing wave; Thermoacoustic cooling

1. INTRODUCTION

Sustainability, green technology, and renewable energy have been among the household words discussed by governments across the globe this last century. The Brundtland Report (also known as Our Common Future) has placed environmental issues on a common political agenda for active participation of all towards a sustainable world. Increasing awareness of the scarcity of energy resources and the environmental degradation has spurred extensive research into alternative clean technologies as well as more efficient energy-related systems. Malaysia, as one of the countries experiencing rapid economic growth with industrialization and urbanization, has recognized the importance of alternatives for energy resources and more efficient energy use despite being an oil and gas producing country. Government research bodies and public universities have been given various grants to conscientiously pursue research and exploration into the sustainable production, processing, and utilization of the Malaysian resources.

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Thermoacoustic refrigeration is an environmentally friendly, robust, and miniaturizable system (Poignant et al., 2010). Although currently not commercially available for the public, successful systems have been completed and used. In 1986, Hofler developed what was probably the first thermoacoustic refrigerator with a cooling power of 6W and 10.2 bar pressurized Helium gas as the working fluid (Hofler, 1986). Garrett et al. (1993) developed the Space Thermoacoustic Refrigerator (STAR) flown on the space shuttle Discovery in January 1992. The system has a cooling power of 5W with a mixed gas of 97.2% Helium and 2.7% Xenon in a 10 atm ($10.1325x10^5$ N/m^2) pressurized resonator. In 2004, Garrett and his team developed a thermoacoustic chiller for Ben and Jerry's ice-cream factory (Poese et al., 2004). The chiller has a cooling power of 119W with Helium gas at 10 atm ($10.1325x10^5$ N/m^2) pressure.

Besides being costly to built, thermoacoustic refrigerators involve complex fluid flow interactions around the stack region. There are also many fundamental issues related to the thermoacoustic effects and the associated heat transfer that must be addressed (Zink et al., 2010). This paper reports some of the results obtained from a series of experiments completed with a portable counter-top thermoacoustic cooling apparatus designed and fabricated at the Universiti Teknologi Malaysia (UTM). Using no refrigerants or compressor, cooling was actually achieved as acoustic waves were generated by a loud-speaker into an air filled cylindrical tube.

2. DESIGN AND FABRICATION

The thermoacoustic system consists of the resonator, the stack, the acoustic driver and the working fluid. A schematic of the system is shown here in Figure 1.

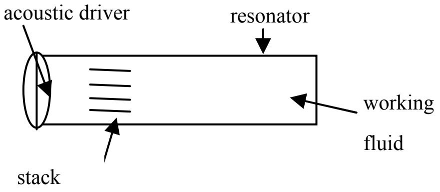

Figure 1 Schematic of a thermoacoustic system

The resonator consisted of a pvc and acrylic tubes. The selection was such that the length, weight, shape and the energy losses are optimal. A thermoacoustic resonator can have either a half (λ/2) or a quarter (λ/4) wavelength length tube. In the boundary layer approximation, the acoustic power lost per unit surface area of the resonator is given by (Swift, 2001),

$$\frac{d\dot{W}_2}{dS} = \frac{1}{4}\rho_m|\langle u_1\rangle|^2\delta_v\omega + \frac{1}{4}\frac{|p_1|^2}{\rho_m\alpha^2}(\gamma-1)\delta_k\omega \quad (1)$$

where the first term on the right is the kinetic energy dissipated by viscous shear. The second term is the energy dissipated by thermal relaxation. Since the total dissipated energy is proportional to the wall surface area of the resonator, a λ/4 length resonator will dissipate only half the energy dissipated by a λ/2 length resonator. Both types of resonators were tried here to show the cooling effects produced. Significant thermoacoustic effects are only produced when acoustic waves are generated at the resonant frequency of the working fluid. This frequency, *f*, or the length of the resonator, *L*, is set before either one value can be determined from the classical relationship,

$$f = \frac{\sqrt{\gamma RT}}{4L} \tag{2}$$

where the denominator is actually the wavelength, λ, set equal to 4 times the length of the resonator for a quarter wavelength standing wave. The values for the ratio of specific heat, γ, gas constant, R, and temperature, T, are taken for air at atmospheric conditions. In this paper, results from experiments completed at various design frequencies are described. Table 1 shows the relevant design parameters of the experiments. A High Density Polyethylene (HDPE) material is chosen for a parallel stack geometry due to its low thermal conductivity. The parallel-plate stack consists of parallel plates which are spaced by fishing line spacers glued between the plates. Using the simplification suggested by Wheatley (Poignant et al., 2010), the plate separation gap would be between two to four times the thermal boundary layer, given by:

$$\delta_k = \sqrt{\frac{K}{\rho c_p f \pi}} \tag{3}$$

The stack center position was then maintained according to Swift's optimized value (Zink et al., 2010) of λ/20. The acoustic waves were generated by a function generator through a loud speaker. Data was collected with air as the working fluid at 1 atmospheric pressure ($1.01325x10^5$ N/m^2) using a scan meter with K-type thermocouples and digital multimeter. The experimental set-up follows exactly that of Mahmood (Anwar, 2009).

Table 1 Design parameters for thermoacoustic set ups

Diameter (D) [$x10^{-3}$ m]	Design frequency(f) [Hz]	Resonator length (L) [$x10^{-2}$ m]	Stack center position (x_s) [$x10^{-2}$ m]
30 (PVC 1)	300	29.1 ($L = \lambda/4$)	5.82 ($x_s = \lambda/20$)
60 (PVC 2)	400	21.8 ($L = \lambda/4$)	4.36 ($x_s = \lambda/20$)
100 (PVC 3)	500	34.9 ($L = \lambda/2$)	3.49 ($x_s = \lambda/20$)
35 ACR 1	400	21.8 ($L = \lambda/4$)	4.36 ($x_s = \lambda/20$)
110 ACR 2	400	43.6 ($L = \lambda/2$)	4.36 ($x_s = \lambda/20$)

3. RESULTS AND DISCUSSIONS

Although systems by past researchers were based on Equation (2) for the operating resonance frequency, some required modifications during their experiments were reported, in order to achieve resonance. In the series of experiments completed in this study, the operating resonance frequencies for the pvc systems were determined from the Mahmood-Normah Correlation (Anwar & Normah, 2009). For PVC 1, the operating resonance frequency was actually 218.8 Hz from the correlation. Significant thermoacoustic effects were noted within 5 seconds after start-up. A maximum of Thot = 31.6^{o}C and minimum of Tcold = 21.7^{o}C was achieved where Tamb was 24.3^{o}C. The pressure-velocity coupled oscillations in a standing wave generated a temperature gradient across the stack placed in the path of the acoustic waves. Figure 2 shows the cooling achieved from the $30x10^{-3}$ m diameter PVC 1 setup designed at 300 Hz and operated at 218.8 Hz. Figure 3 shows a typical pvc set up fabricated for this study.

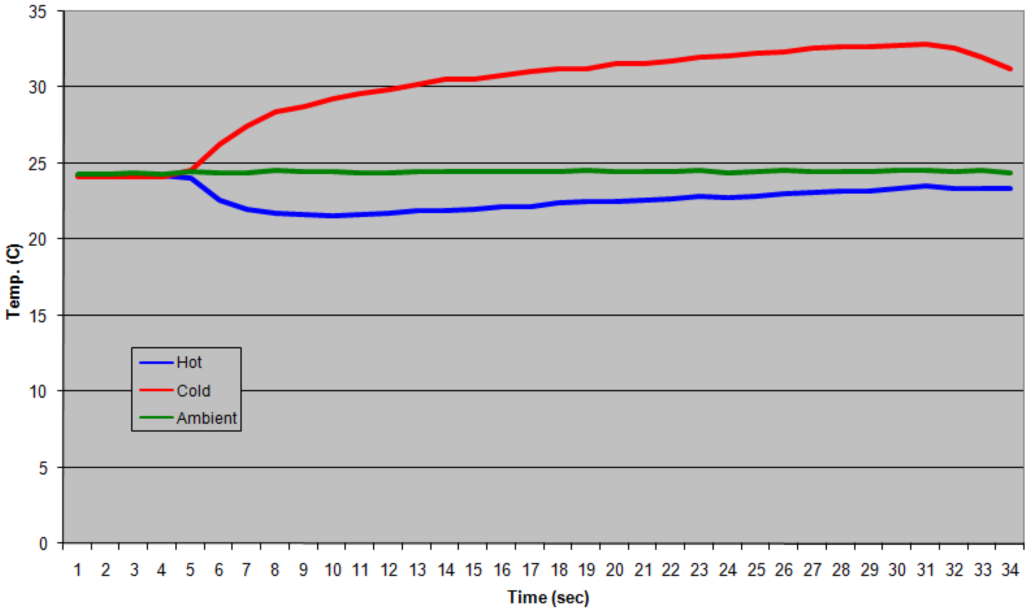

Figure 2 Results from a 30 mm diameter resonator (PVC 1)

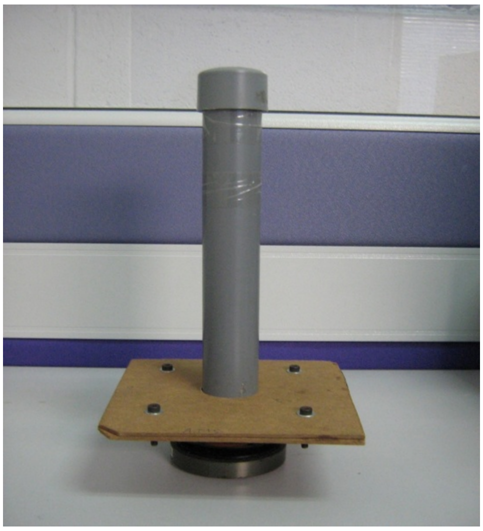

Figure 3 A PVC thermoacoustic resonator

The 400 Hz system (PVC 2), also designed for a quarter wave length standing wave has an operating resonance frequency of 217.5 Hz using the Mahmood-Normah Correlation (Anwar & Normah, 2009). Significant cooling was obtained 40 seconds after start up with Thot = 33.8^{o}C, Tcold = 18.5^{o}C, and Tamb at 24.20^{o}C. Figure 4 shows the result for this $60x10^{-3}$ m diameter resonator.

The third set up, PVC 3, was designed for a half wave length standing wave since the quarter wave length for 500 Hz designed frequency would caused a resonator length to be very short Equation (2). Operation at 147.2 Hz, the operating resonance frequency obtained from the Mahmood-Normah Correlation (Anwar & Normah, 2009), produced a 5 degree cooling below ambient 40 seconds into the experiment. The system achieved a maximum Thot = 32.9^{o}C, minimum Tcold = 19.5^{o}C and Tamb = 24.2^{o}C. Figure 5 shows the result from the PVC 3.

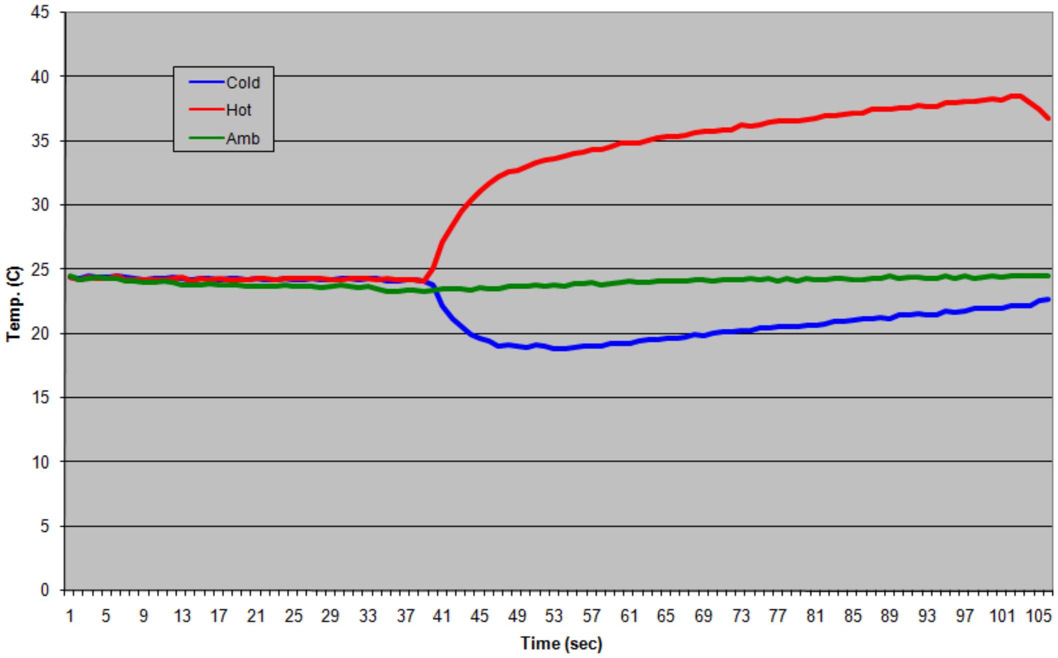

Figure 4 Results from a 60 mm diameter resonator (PVC 2)

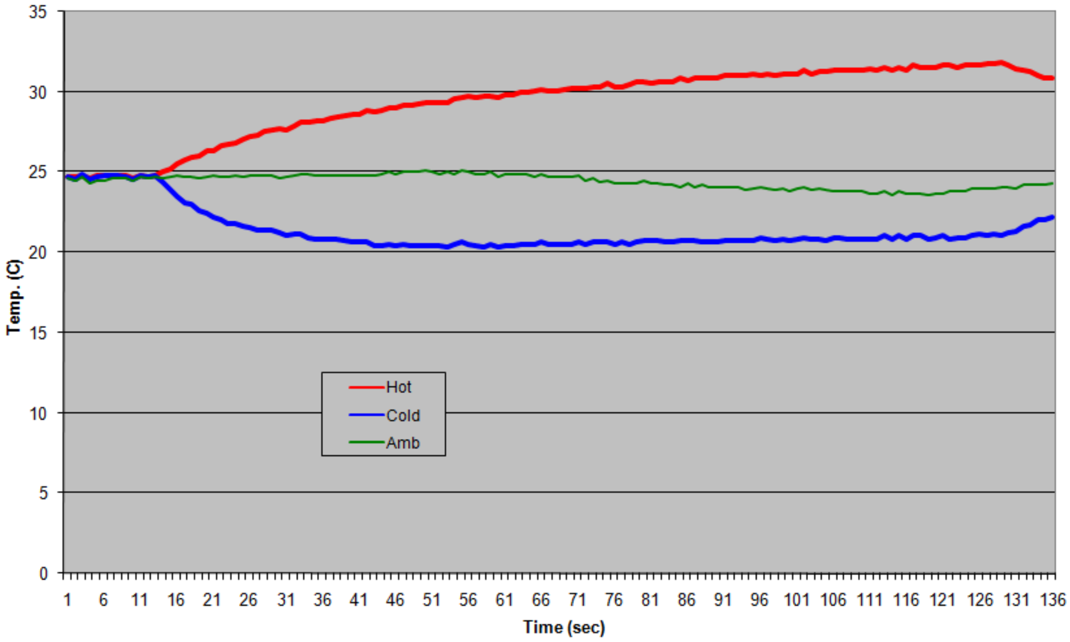

Figure 5 Results from a 100 mm diameter resonator (PVC 3)

The fourth set up was a $35x10^{-3}$ m acrylic tube. The stack geometry and dimensions were similar to those used in the pvc resonators. Using the Mahmood-Normah Correlation (Anwar & Normah, 2009), the operating resonance frequency for the $35x10^{-3}$ m acrylic resonator tube for a 400 Hz design frequency is found to be 217.00 Hz. The maximum Thot was 28.2°C and minimum Tcold was 22.7°C with the Tamb at 24.7°C. Figure 6 shows the counter-top acrylic thermoacoustic system and Figure 7 shows the results obtained. The last system, a $110x10^{-3}$ m diameter acrylic resonator produced the largest cooling effect, 15 degrees below ambient, as shown in Figure 8.

Figure 6 A counter-top acrylic thermoacoustic refrigerator

Cooling of between 2°C to 15°C has been achieved below ambient in all the systems tested. The ACR 1 system had a slightly lower cooling, probably due to the heat transfer losses. The limit to the temperature gradient obtainable is determined by the rate of heat transfer within the stack material itself as well as that to the surroundings. Thermoacoustic occurring elsewhere than within the stack is undesirable, thus a resonator material having close to isothermal conditions is favorable. Acrylic material (KAcr = 0.20 W/m.°C) does have a higher thermal conductivity than that of pvc material (Kpvc = 0.09 W/m.°C). Comparison of the cooling obtained between the quarter wavelength resonator of $29.1x10^{-2}$ m and $21.8x10^{-2}$ m shows that the larger diameter tube gives a better thermoacoustic cooling. The half wavelength system produced the same temperature drop below ambient as the second quarter wavelength system. It could be justified that the losses explained by Equation (1) have been counter balanced by the diameter effect.

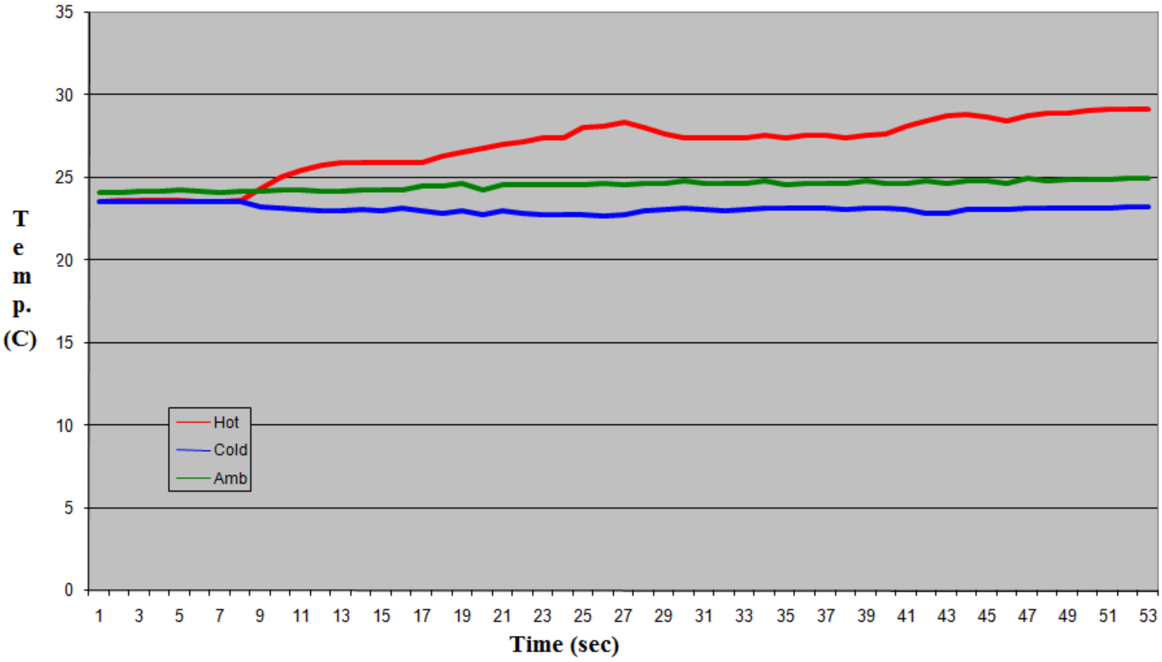

Figure 7 Experimental data from 35 mm diameter resonator (ACR 1)

The experiment with the last set up was completed under atmospheric conditions with air as the working fluid. The experiment was run with a $110x10^{-3}$ m diameter acrylic tube. That produced a temperature drop of 15°C below ambient and the system recorded a temperature of 8°C at the cold side of the stack with Tamb = 23°C. Figure 8 shows the performance of ACR 2. Note that except for the last system, the curves obtained are smooth which would have been absent if the operating frequency was not at resonance. The operating frequency for the last system was not obtained through the Mahmood-Normah Correlation. Designed at 400 Hz, the frequency was just refined through trial and error to see how far the temperature drop could be attained.

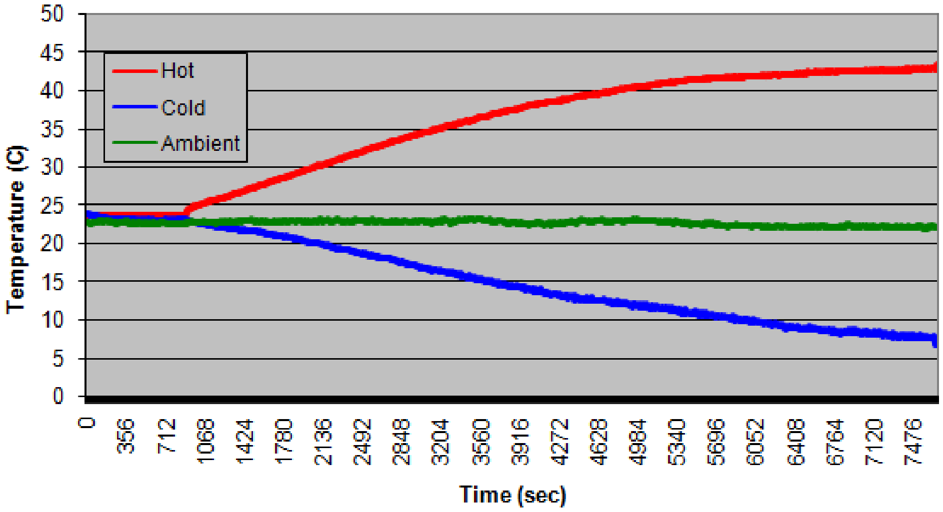

Figure 8 Experimental data from 110 mm diameter resonator (ACR 2)

Operations at the design resonance frequency of Equation (2) would produce thermoacoustic effects but the cooling is very negligible (Anwar & Normah, 2009). However, even with significant cooling effects operating at resonance, the cooling output did not last long due to the heat transfer losses. A larger diameter resonator would prolong the effect. The current study has proven that cooling could actually be achieved without the normal refrigerants or compressor, thus no consequences of the hazardous environmental degradation is expected if such systems can be made practicable. Beside some fundamental issues related to the thermoacoustic effects at resonance frequency, streaming and non-linear effects are other issues that have yet been addressed.

The cooling obtained in the described experiments had been obtained quite simply and at atmospheric conditions. So far, successful systems built operated under high pressure of between 6-20 bar with inert gases such as Helium, Xenon, Argon or a mixture of them. The systems have lower coefficient of performance than the conventional cooling systems, making thermoacoustic refrigeration unfeasible for the open commercial market. The possibility of having such systems without the destructive refrigerants and compressor, however, is attractive in view of the current global awareness and goal for a more sustainable future in energy use and efficiency. This report has proven the potential and that further research needs to be done and should be done to make thermoacoustic refrigeration systems practicable and comparable to the current available systems in specific applications if not in all circumstances.

4. CONCLUSION

Thermoacoustic cooling have been achieved quite simply without any refrigerants or use of a compressor under atmospheric conditions. Although the temperature drop below ambient was small, the clean technology poses as a potentially attractive alternative to the conventional system in view of the increasing concern over the degradation of the environment caused by refrigerants from the cooling industries. Further studies into the control and reliability of thermoacoustic systems could make them comparable to the available systems even for specific purposes if not for general applications.

5. ACKNOWLEDGEMENTS

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