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Seasonal temperature variation in heat collection liquid used in renewable, carbon-free heat production from urban and rural water areas

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Abstract. A renewable energy source called sediment energy is based on heat collection with tubes similar to those used in ground energy and is installed inside a sediment layer under water body. In this paper, an investigation of temperature behaviour of heat carrier liquid is made during several years to evaluate utilization of sediment energy. This is done by evaluating temperature variations of heat carrier liquid and its correlation to air temperature. This increases advancement of knowledge how the temperature of the sediment recovers from the heat collection. The temperature variation of the liquid seems to correlate with the mean monthly air temperature. The selected methods clearly indicate that sediment energy seems to be yearly renewable because there is a clear correlation between air temperature and heat carrier liquid temperature.

Key words: renewable, energy source, carbon-free, heat energy, sediment energy.

INTRODUCTION

New methods and technologies are needed to take advantage of abundance of renewable, carbon-free energy sources existing both in urban and rural areas. This energy is collectable even with small, local distributed systems which makes them suitable even for small applications. These systems can be, for example, solar panels, solar collectors, ground heat collection pipes or wind turbines. These local, renewable systems provide energy independence as well as typically energy-savings in the long term. The initial implementation costs are usually higher than the traditional solutions but as the technology get more common, then its cost should go down. The lack of knowledge as well as a need for more suitable methods limits the utilization of renewable sources.

One of the new methods is a heat energy collection system from solid, organic sediment layers at bottoms of water bodies using pipes and heat carrier liquid (Hiltunen et al., 2014). Specially designed pipes are installed horizontally into the sediment layer, 3–4 meters under the bottom of the water body. The heat is then collected by the heat carrier liquid like it is done for other ground heat systems. A COMSOL model of the system has been implemented to study the heat extraction and behaviour of the system (Haq et al., 2014). Since the heat is extracted from a layer consisting of sediments, the approach is named as ‘sediment energy’. This energy is renewable: the heat energy of sediment layer comes mainly from the Sun and only a minor part is from the Earth’s own geothermal energy. The layer gets warmer during summer and release heat during winter. Since the density of water is highest at +4 °C, the bottom of the water body is at this temperature and forms a natural limitation to heat release from sediment during winter time. The ice cover and snow over the water body may also have a significant effect especially in shallow and small lakes in arctic areas (see e.g. Tsay et al., 1992). Models for the warming and cooling cycle of lake sediments has been suggested many authors like e.g. Fang & Stefan (1998) or Golosov & Kirillin (2010).

A heat collection system should be able to operate in the long term and preferably to be able to replace the taken heat energy. Thus heat extraction from the sediment layer is a critical factor for the sediment energy system to operate. The suitable heat extraction rate needs to design correctly in order not to overuse the heat source. On the other hand, undersizing the system will increase costs of implementation. To study the heat extraction, the liquid temperature is measured for a period of several years. This will cover the natural yearly variation in air temperature and other weather conditions.

The evaluation is done in three parts. First, the minimum temperatures of the heat carrier liquid is searched as the minimum operating liquid temperature for the system should exceed -15 °C. Second, the durations of cold (temperature below 0 °C) and warm periods for liquid are evaluated. If the durations of cold periods were to get longer in the course of years then this would indicate overuse of the source. Third, the correlation between air temperature and liquid temperature is calculated with Spearson's and Pearson's coefficient (Sprinthall, 2012). This is very important for sediment energy since its renewability depends on complex interaction between air, water, sediment and sun. Of course, some investigation between air temperature and heat carrier liquid has been done for example a helical heat exchanger (Zarrella & De Carli, 2013) but not for sediment heat energy system as this is a very new invention.

The results demonstrate the suitability of sediment energy for long term use. This information is important to designing the suitable heat extraction rate as well as evaluating the available heat energy capacity. The liquid temperature information has been collected from a pilot system installed in 2008 at the Suvilahti suburb and sediment layer of seabed of Suvilahti bay, Vaasa, Finland. The pilot system supplies heat and service water for a very small district with 42 houses. The initial usability of the system has been demonstrated by measuring the sediment temperatures as well as showing the energy consumption (Hiltunen et al., 2014).

SEDIMENT ENERGY COLLECTION SYSTEM

The prototype system consists of 26 pipes shoved into the sediment layer, 2 heat collection wells at Suvilahti shore and 12 distribution wells. The pipes are designed especially for sediment layers and a sectional view is shown in Fig. 1a. Five outer chambers of the pipe will carry a cooler heat carrier liquid while the warmed liquid will return through the inner chamber.

The pipes were installed at a fan formation as displayed in Fig. 1 b. At the seaside, the pipes are approximately 3–4 meters depths from the bottom of the water layer. An optical cable was installed with a pipe for temperature measurement of sediment near the pipe. At the shore side, the pipes are connected to the heat collection wells which are then connected to distribution wells. The distributions wells then deliver warmed liquid for household use. The system has also been used for cooling in the summer time.

The carrier liquid is currently a mix of water and ethanol. The frost resistance of the mixture is -15°C which allows the operation even if the sediment freezes.

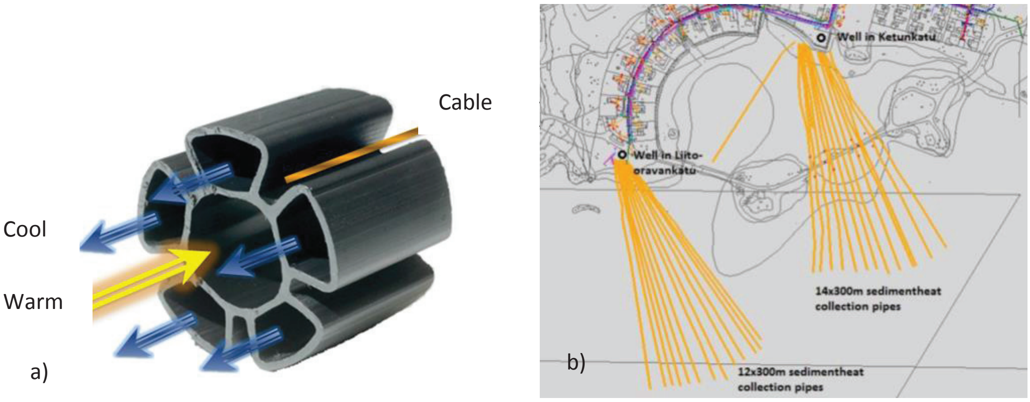

Figure 1. a) Heat collection pipe has a special structure designed for heat extraction from sediment with 5 outer and 1 inner chambers; b) Together 26 collection pipes were shoved into sediments (Mauri Lieskoski private communications; source of the figure: Vaasan Eko-lämpö Oy).

TEMPERATURE DATA OF AIR AND HEAT CARRIER LIQUID

Temperature data from sediment has been collected also earlier but their purpose has been different like for modelling (Golosov & Kirillin, 2010) or for temperature variation at different depths of surface (Banks, 2012). In our approach, we have collected temperature values of heat carrier liquid which correlates with temperatures of the sediment, to study recovery of sediment temperature. Of course, this is done during the heat collection for the district.

The temperature data for this study was obtained from Finnish Meteorological Institute. This is official, quality controlled data and it is measured according to ISO9001:2008 and WMO-No.8, CIMO Guide. The temperature was given as a monthly average as we have assumed that total heat energy matters more than a short, temporary variations like diurnal changes. Temperature of the liquid has been monthly recorded with Ouman temperature measurement device between years 2008–2013.

THEORY AND MODELLING

The suggested physical explanation for the liquid temperature is that the heat carrier liquid collects heat from the sediment inside the seabed. The sediment is warmed up directly by the conduction of the Earth's geothermal energy (small amount), and indirectly by solar energy (main cause). The Sun warms air and water, and water then conveys the heat energy to sediment. It is also possible that some solar radiation reaches the upper layer of sediment. During the winter time, the usage of sediment energy is greater and thus more heat is extracted. Since the heat energy at the sediment is limited and its diffusion is relatively slow, the liquid gets colder. Some of the sediment heat also dissipates back to water.

To be usable energy source, sediment energy should be annually renewable and sustainable– i.e. its heat energy comes (mainly) from the Sun. The interactions between the Sun, air, water, and underwater sediments are, however, very complex and difficult to model. Therefore, the temperature variations of liquid and air are used for the evaluation as they are easy to measure. The goal is to study that enough sediment energy is available for years and it is correlated to air temperature which then depends on the solar radiation. This correlation is assumed to be due two factors: interaction between water and thus sediment, and an increased need of heating houses during winter due to crease in solar radiation. The need of hot service water is, of course, all-year.

The renewability and use of sediment energy is evaluated by inspecting the length of periods with positive and negative temperatures. This is a very simple test. If the length of periods for liquid temperatures stays approximately the same in different years, then this is very like due the annual renewal of sediment energy. It also implicates that there is no overuse. A sum over each period is calculated and this approximates an integral over the period. This evaluation method was selected because shape of periods varies and they cannot be directly compared.

The correlation between air temperature and liquid temperature may implicate that the solar radiation is the main source of heat in the sediment. Pearson product-moment correlation coefficient and Spearman's rank correlation coefficient were chosen to study this correlation. They are shortly described here; a more comprehensive overview can be found many statistical textbook (e.g. Sprinthall, 2012).

Pearson product-moment correlation coefficient (Pearson *r*) is used to measure linear correlation or dependence between air temperature (symbol *x*) and liquid temperature (symbol *y*). The values can be between +1 and -1 where 1 is total positive correlation, -1 total negative correlation and 0 is no correlation. The Pearson *r* is defined as:

$$r_{x,y} = \frac{cov(x,y)}{\sigma_x \sigma_y} = \frac{E[(x-\mu_x)(y-\mu_y)]}{\sigma_x \sigma_y}, \tag{1}$$

where: *cov* indicates covariance; σ is the standard deviation; μ is mean; *E* is expectation; subindex *x* indicates air data; and subindex *y* indicates liquid data. It is assumed here that the entire range of air and liquid data can be presented as normally distributed. The temperature values naturally belong to interval data.

The significance of Pearson *r* is tested against the null hypothesis: the correlation is due to change. The significance can be assessed using Pearson *r* table with the degree of freedom (the number of pairs of scores minus 2) (Sprinthall, 2012).

Another selected metric is Spearman's rank correlation coefficient (Spearman's r_s) which is a nonparametric measure. Both air and liquid temperature values are converted into ordinal ranks. For each month, the absolute difference *d* between air and liquid temperature ranks is calculated and squared. The Spearman's r_s is calculated using the following formula:

$$r_s = 1 - \frac{6\sum d^2}{N(N^2-1)}, \tag{2}$$

where: *N* is the number of pairs. It is used here to evaluate the statistical dependence between air and liquid temperatures: it compares their relationship to a monotonic function. The values are again between +1 and -1.

RESULTS AND DISCUSSION

The original data of mean air temperature per month and liquid temperature is plotted in Fig. 2. Both data have a seasonal, cyclical variation. The highest liquid temperature was obtained in summer 2009 (12 °C) when the system had been used in very short time. The lowest value is -2.0 °C which was obtained 2010 January and February. The liquid achieve its maximum temperature typically after one month of the peak value for air temperature. However, the minimum liquid temperature stays between 0 and -2 °C in winter time although the system is in full use. Since the minimum value stays over the critical liquid limit temperature of -15 °C, the system operates without problems.

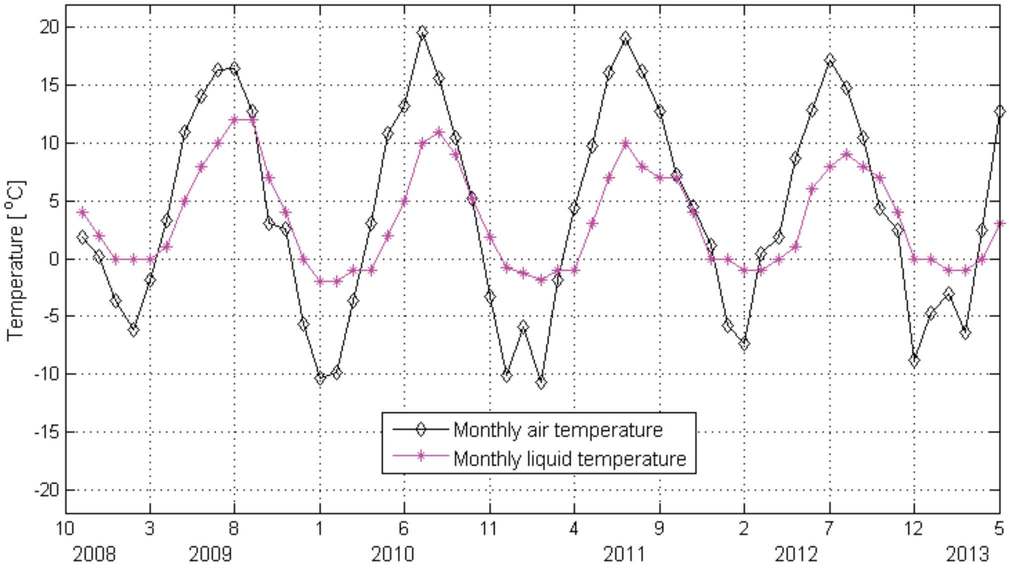

Figure 2. Both the mean air temperature as well as the temperature of heat carrier liquid show clear cyclical variation as a function of season.

Fig. 3 visualizes the length of cold and warm periods for both air and liquid. A period consists of months which mean temperature either exceeds 0 °C (‘warm period’) or is below 0 °C (‘cold period’). The value of 0 °C was selected because it is the freezing point of water. It is of course possible to select another limit value but the goal here is look at trends existing in data. As can be seen from Fig. 3, there is clearly natural variation in lengths of air temperature periods. The mean temperature sum for cold and warm periods is shown in Fig. 4.

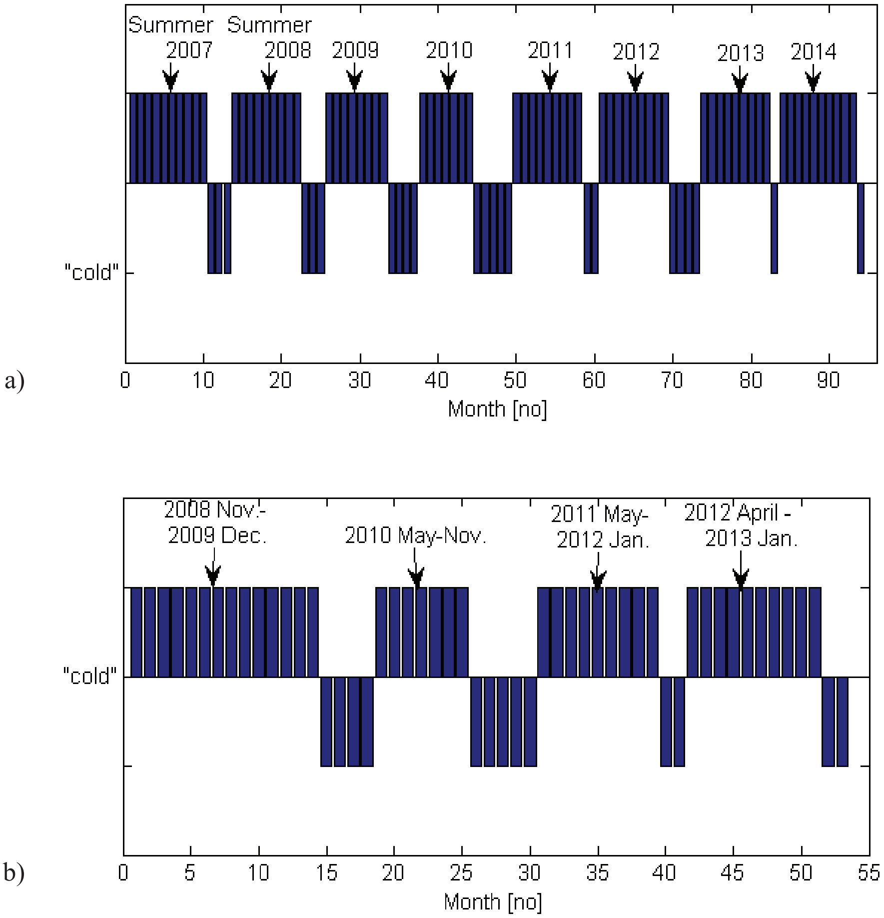

Figure 3. The length of positive and negative temperature periods is visualized for a) air temperatures and b) liquid temperature. One bar indicates one month.

The same data is in numerical format in Table 1. The mean value for warm period temperature sum is 80.4 °C and standard deviation 5.6 °C. For cold period sum, the mean value is -15.8 °C and standard deviation 11.0 °C. The sum of mean temperatures varies more between cold periods than between warm periods. This is due to natural variation between years and it probably has some effect on amount of heat energy in sediment. The length of negative period for liquid temperature has recently got shorter, only 2 month length as shown in Fig. 3b. Also the sum of negative temperatures has decreased.

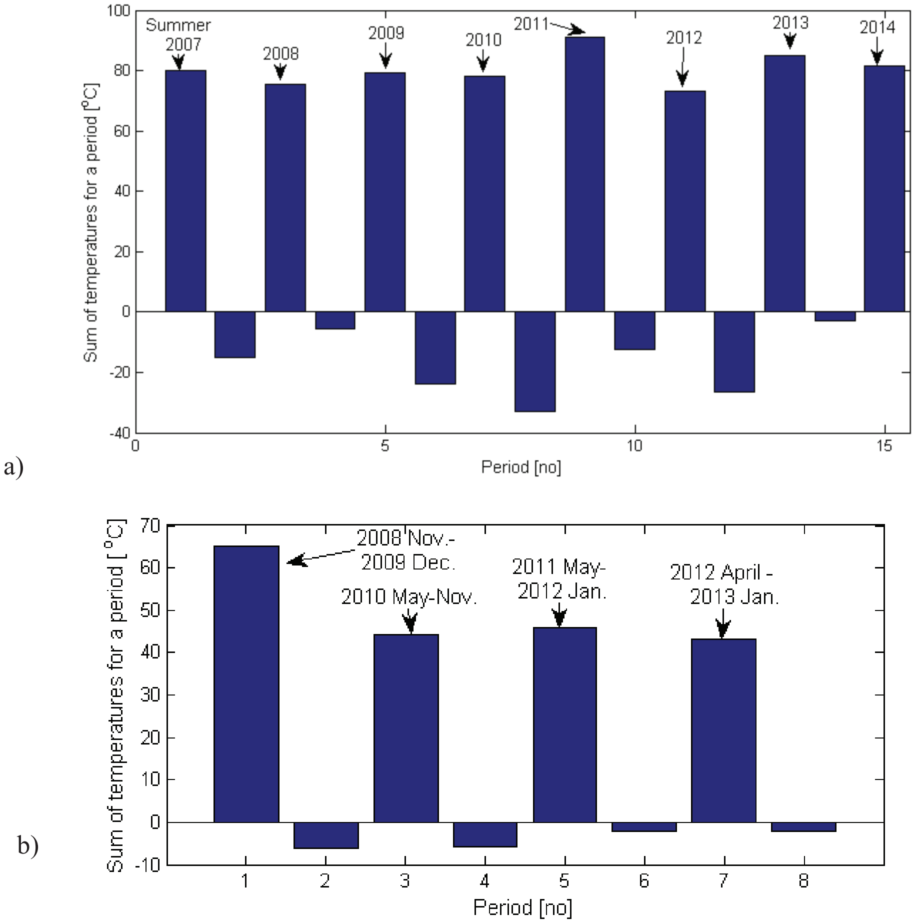

Figure 4. The sum of mean temperatures is calculated for a) air temperatures and b) liquid temperatures. The sum of mean air temperatures has a greater variation between the cold periods than the warm periods.

Table 1. Numerical values for period lengths and temperature sums

Parameter/period	Length (month)		Sum of temperatures (°C)	
	Air	Liquid	Air	Liquid
2007 warm	10	NA	79.9	NA
2007-2008 cold	3	NA	-15.1	NA
2008 warm	9	NA	75.6	NA
2008-2009 cold	3	NA	-5.6	NA
2009 warm	8	12	79.4	65.0
2009-2010 cold	4	4	-24.0	-6.0
2010 warm	7	7	78.0	44.1
2010–2011 cold	5	5	-32.8	-5.9
2011 warm	9	9	91.0	46.0
2011–2012 cold	2	3	-12.5	-2.0
2012 warm	9	10	73.1	43.0
2012–2013 cold	4	2	-26.6	-2.0

This indicates that the heat energy is renewable and available for longer term use as well as not overused in addition to the fact that the system is still currently used.

It is also possible to calculate correlation between monthly air temperature and temperature. First, the linearity between these variables is investigated by plotting them as shown in Fig. 5. Since variables seems to be linearly related. Thus, both selected statistical metrics should produce valid results. Fig. 6. shows results for Pearson's and Spearman's coefficients. When the both data is taken from the same month, Pearson value is 0.8571 (p-value 6.7744e-17) and Spearman value is 0.8640 (2.0105e-17). If the liquid data is taken from the next month, then the values are even higher: Pearson 0.9319 (1.4481e-24) and Spearman 0.9347 (5.1819e-25). Tables gives critical values ($N = 55$) 0.338 for Pearson coefficient ($\alpha = 0.01$) and 0.346 for Spearman's coefficient ($\alpha = 0.01$). This indicates are surprisingly high correlation.

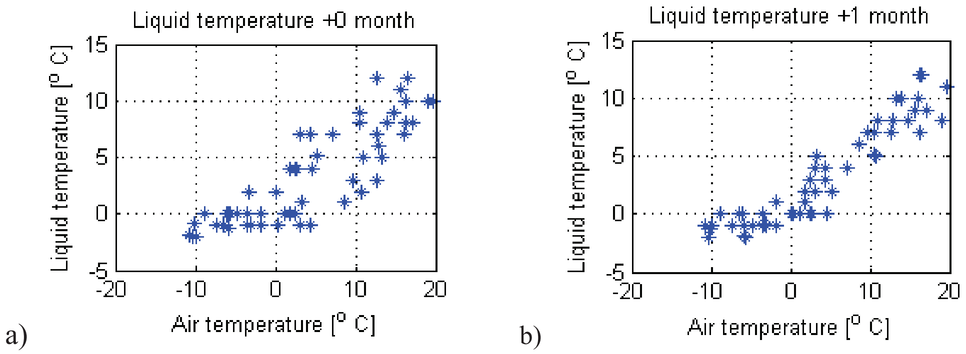

Figure 5. Mean air temperature is plotted against liquid temperature. In a) both temperatures are measured in the same month while in b) liquid temperature of the next month is plotted against air temperature.

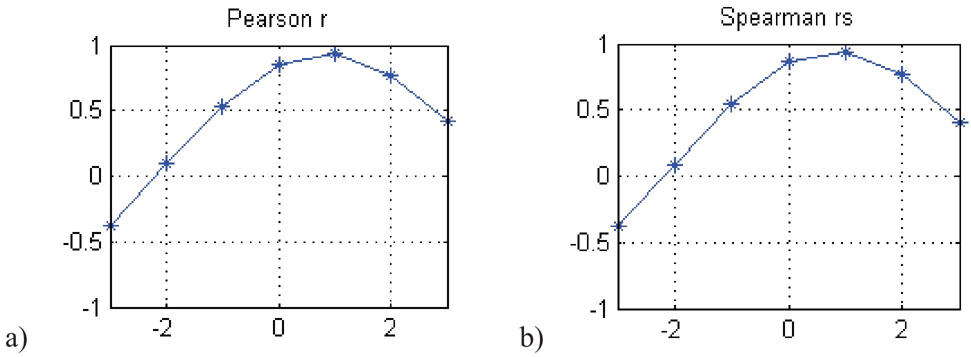

Figure 6. a) Pearson r and b) Spearman's r_s both indicate high correlation between air temperature and liquid temperature. The correlation is highest between air temperature and next month's liquid temperature. The x-axis indicates whether the air data is correlated with liquid data value delayed or furthered. When it is zero, both liquid and air data is from the same month.

CONCLUSIONS

During the first years of the studied periods, the minimum value of the liquid temperature was -2 °C which is well above the critical system operation temperature of -15 °C. The absolute difference between these two values is over 10 °C, so there system has still a buffer for a greater heat extraction. During the last part of the periods, the minimum value of liquid temperature has been even closer to zero and the duration of periods of negative temperatures has been shorter than earlier. This all indicate that the sediment energy system is stable and renewable.

The correlation between monthly mean air temperature and liquid temperature has been studied using Pearson's and Spearman's coefficient since the temperature data seems to have a linear dependency. The both coefficient indicate a strong correlation and it is significant.

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