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# Performance analysis of Gravitational water vortex power plant using scale-down model

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**Abstract**— Gravitational water vortex power generation plant is ultra-low head micro hydro concept which requires mere 0.7-2m of height. GWVPP is based on the principle of power generation with rotation of turbine with the help of vortex generated due to basin structure when water can pass tangentially. This technology is in a primitive phase of development in various part of world. So, developers across the world are interested on how it performs in real site as only few real installations have been made far. This paper attempts to analyze the performance of different scale down model of GWVPP. First, the performance is compared among various experimental studies and pilot installations done so far in Nepal. After that the analysis of different computational studies is performed. To accesses the validation of the result obtained from the past researches, 1:20 scale down model of a plant which is to be installed in Johannesburg South Africa is developed and whose computational and experimental result is compared and predicted the model performance.

## 1. INTRODUCTION

With an average of the 1% increment in the global energy demand per year, the electrical power demand is increasing even faster [1]. We still have 1.2 billion people around the world who do not have access to electricity, and 85% of them live in rural areas [2]. The best solution for providing them with electricity is Rural electrification. It is the only way to provide electricity to those rural areas as they lack the grid or may require huge capital to connect to the grid [3]. Many of the novice sites for hydropower development are expected to be suitable for the small micro-hydro systems (less than 100 kW) [4] to electrify the rural area. Researcher today, are interested in low-head sites ( 0.8 m to 2 m) micro hydro system that are cost efficient and easy to be installed in remote places. [5].

Some major concerns related to MW-scale hydroelectric plants are the disturbances they pose to the environmental balances. For example, the river ecosystem gets destructed due to the deviation of conventional water flow and the construction of the large dams required for MW-scale plants. These sorts of problems are eliminated by the small micro-hydro systems. Therefore, this system is thought to be highly suitable for isolated rural areas of Nepal and such system has already seen implemented in many parts of the world like Europe, South America, and so on [6].

A process of initiating and mining energy from water vortices for micro hydropower generation, known as the Gravitational Water Vortex Power Plant (GWVP), was developed by Franz Zotlöterer, an Austrian engineer [5]. His design consists of a rectangular canal, a round basin structure, and a turbine. At first, a powerful water vortex is formed by feeding water through the canal tangentially into the basin. Thus formed water vortex, generates kinetic energy. Such energy is converted to electric energy through the turbine runner situated in the center of the water vortex. At the bottom of the basin, an outlet tube is placed, through which the water vortex discharges[7].

Contrary to other micro hydro power plants, which work on the pressure differential across the turbine runner blades to create the torque on the output shaft, Gravitational Water Vortex Power Plant operates through the dynamic force produced by the vortex. The turbine system does two major things i.e. produce a useful output power and aerate the water. Thus, this turbine is regarded as a milestone in hydrodynamic development, as previously energy was required to aerate water but this technology uses a water aeration process to extract electrical energy. This technology is already popular in Europe with more than 50 GWVPPs installed since 2007 and more are under construction.

However, the number of such installations is very few in other parts of the world. The GWVPP has the greatest potential at low-head sites than other hydro power technologies. Unlike conventional reaction or impulse turbines, GWVPP has a potential for maintaining high efficiency even as the head approaches nearly zero. This is because the head is needed just to create an artificial vortex and there is no other significant importance of the higher head for these types of turbine systems[8].

## 2. REVIEW OF PAST LITREATURE

This technology has been lately developed in comparison to other micro hydro power technologies. However, numerous researches have already been done on this technology. We can find numerous research on GWVPP based on Nepal, where other micro hydro power technology has been successfully commercialized since a half century ago[9]. But in 2016, Rabin Dhakal et. al implemented a 1.6 kW pilot project in a river stream to initiate the research based on site implementation [10]. This research is focused on the development of GWVPP in context of Nepal and detect the possible installation sites. Another research of him suggested that existing reservoir sites, existing irrigation canal sites, and existing weir structure sites are three different possible sites having existing water infrastructure for site implementation of gravitational water vortex power plant [11]. Another research conducted by AK Jha et. al. performs a technical and economic assessment of installing 1kW size GWVPP in an irrigation canal in Nepal[12]. This research concludes that the majority of site installation cost accounts for civil cost and pilot installation cost, which is quite high. But still, it opened the door for other real future installations.

We can also find a few literatures regarding the performance analysis of GWVPP based on site installation other than Nepal. Vladimir et. al conducted research based 10-kW-scale GWVPP constructed on a river in rural Peruon[3] and finds that labor was the main cost for site implementation of GWVPP, and considering the challenging high-torque operating conditions, power transmission from the turbine to the generator is a major limitation of this system.

## 3. THEORETICAL DESIGN OF BASIN & RUNNER

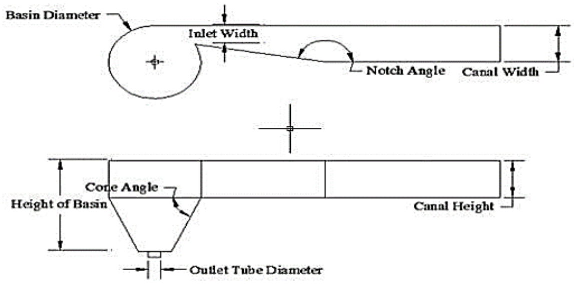


**Figure 1.** Illustration of several geometrical parameters of basin structure implemented in the past studies [5]

The design of conical basin geometry in the current study was based on a simple scroll type vortex drop shaft with a flat bottom that ensures subcritical approach flow condition. Flow is directed to the conical chamber through the tangential inlet of width (inlet width in figure 1 and discharges vertically through the orifice of conical shape. It is assumed that the flow was axially symmetric around the orifice center, the energy head E was constant throughout the flow field, the pressure p inside the air core was atmospheric, the flow was fully hydrostatic and irrotational so that the tangential velocity distribution, v(r), at the throat was given by

$$V(r) = \frac{\Gamma_\infty}{2\pi r} \qquad (1)$$

where v = tangential velocity at radial distance, r, from the scroll axis. A generalized solution for Q [13]can be obtained by considering no loss of energy between the inlet and at the orifice implying that the energy everywhere (Bernoulli's principle) is :

$$E = \frac{V^2}{2g} + \frac{\omega^2}{2g} + \frac{p}{\rho g} \qquad (2)$$

where g = gravitational constant; w = axial velocity; and ρ = fluid density. A property of the irrotational flow field is that for all points on an arbitrary horizontal plane:

$$\frac{V^2}{2g} + \frac{p}{\rho g} = \text{constant} \qquad (3)$$

Hence, when considering Eq. (2) at the orifice, it is easy to show that the axial velocity field, w(r), is constant across the cross section at conical basin. Therefore, by continuity

$$Q = \frac{\pi}{4}\,\omega_0(d^2 - a_c^2) \qquad (4)$$

where wo = axial velocity in the conical basin; d = outlet orifice diameter; and $a_c$ = air core diameter at the orifice. Imposing the atmospheric pressure boundary conditions at the air core interface in Eq. (2) produced the following expression:

$$E = \frac{\Gamma_\infty^2}{2g\pi^2 a_c^2} + \frac{\omega_0^2}{2g} \qquad (5)$$

Combining Eqs. (4) and (5) and solving for Q yields

$$Q = \frac{\pi}{4} d^2(1-\lambda)\sqrt{2gE - \frac{\Gamma_\infty^2}{\pi^2 d^2 \lambda}} \qquad (6)$$

where $\lambda = a_c^2/d^2$ is the fraction of the air core to orifice cross section. Eq. (6) is the general solution for flow in a full air core vortex and is dependent on the three unknowns ($\lambda$, E, and $\Gamma\infty$).

We considered the inlet and outlet velocity triangles for an impulse type turbine runner as the reference to design the runner for this experiment. In Fig. 2, the runner tangential velocity is represented by u, v is the absolute jet velocity, the relative velocity of the jet with respect to the runner is depicted by R, $v_w$ is the whirl velocity, and subscript 1 with all the variables denotes the runner inlet and the subscript 2 with all the parameters depicts the runner exit. Neglecting the runner blade losses, it is normally assumed that $R_1$ is equal to $R_2$.

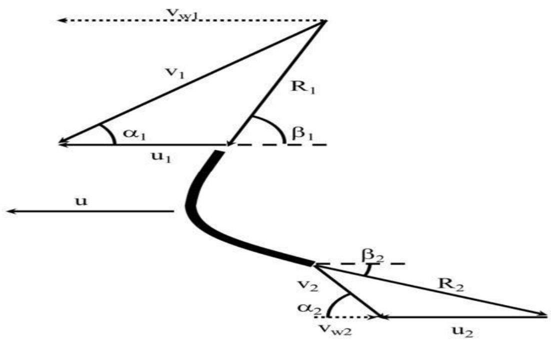


**Figure 2.** Illustration of Inlet and outlet velocity triangles and related parameters for an impulse turbine runner. [6]

The fluid stream experiences a deviation when the high velocity fluid hits the runner. This incident causes a change in momentum on the fluid, exerting a reacting force on the turbine runner. During the design of GWVPP runner blade, the same principle was followed.

In the GWVPP, water moves in both horizontal and vertical direction. However, in the case of Pelton Wheel, the unidirectional flow of the water is assumed. To handle this contradiction, we assume that most of the energy of water is on the horizontal side and the contribution of the vertical side is negligible. Not only this much, the inlet velocity of an impulse turbine is constant. But in case of GWVPP, the inlet velocity changes across the vortex radius, as described by equation (1). This is the reason for the variation of velocity triangles across the radius.

## 4. MODEL SCALING

Scaling down of a prototype reduces the time consumption and eases the computational processing. It is difficult to simulate under the actual condition in CFD. Various experimental tests can be conducted on the scale down model and similitude concept can be used to relate with the large prototype. For the flow that occurs through open channels and where gravitational force is most significant Froude number governs the dynamic similarity [14]. From the equivalence of Froude number

$$\frac{V_m}{\sqrt{gL_p}} = \frac{V_p}{\sqrt{gL_p}} \qquad (7)$$

The scaled down model following geometric, kinetic and dynamic similarity is prepared in the Design Lab of Kathmandu University by 3d printing and testing procedure is facilitated by the preparation of small water reservoir in Vortex Energy Solution Pvt. Ltd. for testing in reduced discharge. The prototype which is a reference for model is obtained from Vortex Energy Solution design team. The prototype is to be installed in 12 kW project at Johannesburg South Africa. The dimensional similarity in model and prototype is expressed in the following table:

| Dimension | Model | Prototype |
|---|---|---|
| Total height | 135 mm | 2700 mm |
| Conical Height | 117 mm | 2350mm |
| Inlet Diameter | 110.5 mm | 2210 m |
| Outlet Diameter | 24.86 mm | 497.25 mm |
| Channel width | 35 mm | 700 mm |
| Channel height | 50 mm | 1000mm |
| Cone Angle | $67^0$ | $67^0$ |

**Table 1.** Dimensional Similarity of Model and Prototype (1:20 scale)

*4.1. Computational Study of Model*

Computational fluid dynamics (CFD) is used to study the flow on the turbine. A CFD process mainly takes place in three distinct steps. First, the boundary conditions are specified by preprocessing step, which is followed by the solver step. Solver step is responsible for portraying the convergence criteria. Finally, the post processing step takes place in which the obtained outcomes are analyzed [15] . We assumed the water vortex as steady, axisymmetric, and incompressible flow.
Following equations define the continuity equation and the Navier-Stokes equations in cylindrical coordinate system.

$$\frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z} + \frac{V_r}{r} = 0 \qquad (8)$$

$$V_r \frac{\partial V_\theta}{\partial r} + V_z \frac{\partial V_\theta}{\partial z} + \frac{V_r V_\theta}{r} = v\left(\frac{\partial^2 V_\theta}{\partial r^2} + \frac{\partial V_\theta}{r\,\partial r} - \frac{V_\theta}{r^2} + \frac{\partial^2 V_\theta}{\partial z^2}\right) \qquad (9)$$

$$V_r \frac{\partial V_r}{\partial r} + V_z \frac{\partial V_r}{\partial z} - \frac{V_\theta^2}{r} + \frac{\partial \rho}{r\,\partial z} = v\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{\partial V_r}{r\,\partial r} - \frac{V_r}{r^2} + \frac{\partial^2 V_r}{\partial z^2}\right) \qquad (10)$$

$$V_r \frac{\partial V_z}{\partial r} + V_z \frac{\partial V_z}{\partial z} - \frac{\partial \rho}{\rho\,\partial z} = g + v\left(\frac{\partial^2 V_z}{\partial r^2} + \frac{\partial V_z}{r\,\partial r} + \frac{\partial^2 V_r}{\partial z^2}\right) \qquad (11)$$

Where, ν is kinematic viscosity, $V_\theta$ shows the tangential velocity component, Vr illustrates the radial velocity component, and Vz is the axial velocity component. We cannot obtain the analytical solution directly due to the complexity of these equations. Therefore, we used CFD method to approximate their solutions.

At first, we created a fluid domain in SolidWorks, which was imported to ANSYS CFX. After that, we produced uniform meshing by discretizing the imports into smaller units using hex dominant meshing. During this process, the free mesh type was set to “All Quadrilaterals”. For the stationary domain of the inlet boundary conditions, we specified a mass flow rate of 0.0315 kg/s. Similarly, we characterized a static pressure of 1 atm for the outlet condition. For validation, we used the turbulence model k-Epsilon since the incompressible water flow is considered. The process was allowed to iterate up to 300 times with RMS residual type and the residual target of 1.0e-4.

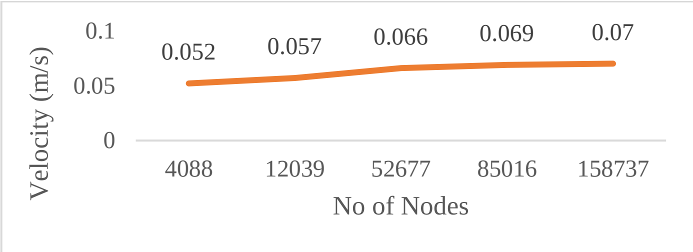


**Figure 3.** Grid Convergence Test

The Computational fluid dynamics was studied on no-slip conditions at the wall and pressure outlet condition at the outlet. The inlet was velocity inlet with initial inlet mass flow rate of fluid (water) is set to be 0.0315 kg/s. The upper surface was subjected to atmospheric pressure. The no. of elements in the final computational domain used for the simulation was 158,737.

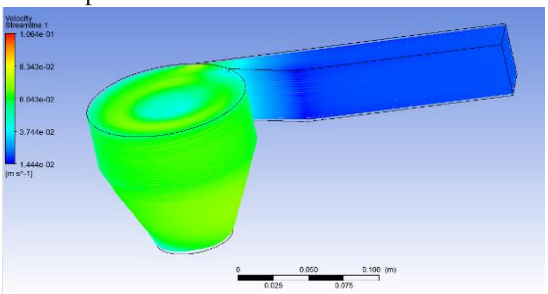

**Figure 4.** Streamlines of Velocity

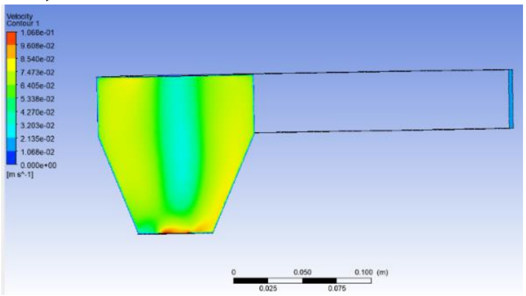

**Figure 5.** Velocity contour

Velocity streamlines and contour is studied in 1:20 scale down model of GWVPP, dimensions are available in table 1. The velocity at inlet position was observed as 0.02m/s and due to cylindrical structure of basin, vortex is generated which results in increase in velocity at runner position to 0.07m/s. With the increase in velocity at the runner position, runner was observed with 200rpm of rotations. With this flow simulation study, it was observed that velocity at runner position increases by 3 to 5 times than that at the inlet position.

### *4.2. Comparison with past computational studies in Nepal*

There are numerous computational studies done on Nepal on the conical basin structure. The inlet velocity and velocity at the runner position is compared in the table below. Moreover, the scale of those as per the proposed installation prototype at Johannesburg is also calculated.

| Studies | Scale | Inlet Velocity (m/s) | Velocity at Runner Position m/s | Ratio |
|---|---|---|---|---|
| Dhakal.S et. al.[14] | 1: 3.375 | 0.1 | 0.375 | 1:3.75 |
| Dhakal. R et. al [16] | 1: 6.75 | 0.3 | 1.3 | 1: 4.33 |
| Current | 1:20 | 0.02 | 0.07 | 1: 3.75 |

**Table 2.** Comparison of different computational studies in Nepal

The velocity of runner position at different scale down model suggested that the velocity at different scale down model has different value. At some point of scaling the velocity increased but again it is decreased.

*4.3. Experimental Testing of Model*

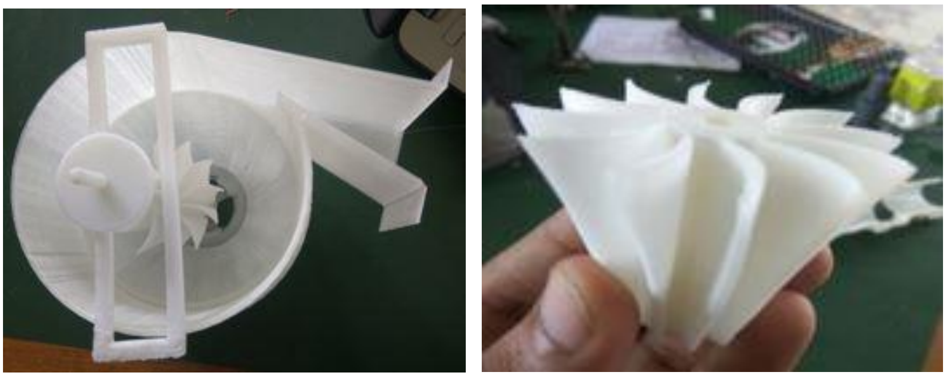

**Figure 6.** 3D printed assembly and runner

For scale down model analysis, the reduced scale down mode of 1: 20 ratio was fabricated at Design Lab, Kathmandu University. The material used was Transparent PLA. Our objective was to test the setup for a free flow. We used water pump that could discharge water at the rate of 0.02 liter per second. Drop box was used in the experimental testing of the scale down model for continuous and adequate flow of water.

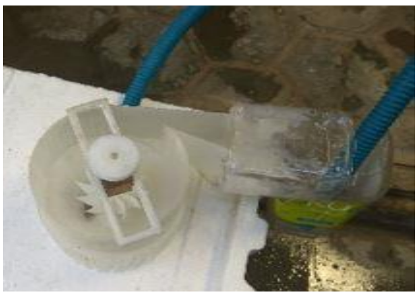

**Figure 7.** Experimental Setup

The speed was measured by tachometer which is available in the TTL whereas torque was measured using Rope Brake Dynamometer method. The torque produced was calculated by using the simple mathematical relation of rope brake dynamometer method i.e. Torque (T). = r(W1-W2)Where W1 and W2 is load applied at end of the rope and the spring balance reading respectively and r is the radius of the brake drum (pulley) [17]

Power in the shaft is calculated by:

$$P = \frac{2\pi NT}{60} watts \qquad (8)$$

Where N is the RPM measured by tachometer. The input power (hydraulic power) is calculated as:

$$P_{in} = \rho Qgh\, watts \qquad (9)$$

Where ρ is the density of water, 997 kg/m3 Q is the flow rate, - l/s & g = 9.81m/s2s

| Studies | Scale | Inlet Velocity (m/s) | Max. Rpm | Efficiency % |
|---|---|---|---|---|
| Dhakal.R et.al [18] | 1:1.8 | 0.2 $m^3/s$ | 95 | 70.9 % |
| Dhakal.S et.al. | 1:3.375 | 0.1 | 174 | 36.84 % |
| Dhakal.R et.al. | 1:6.75 | 0.03 | 140 | 28.4 % |
| Current | 1:20 | 0.002 | 200 | 12.1 % |

**Table 3.** Comparison of different experimental studies in Nepal

## 5. DISCUSSION

The analysis of the performance of the proposed installation by the study of performance on the scale down model has been a proven technique. But analysis of these type of ultra-low head system has not been so far. This section of the paper discusses the performance of different scale down model which would be a step for the prediction of the performance of real scale installation.

### *5.1. Performance of Turbine (Mechanical System)*

The performance of a turbine depends on various factors like inlet flow, the height of the basin structure and outlet tube conditions. Although the four studies taken for the analysis in Table 3 have geometric similarities, the inlet velocity is different due to different inlet flow conditions. The kinematics similarities are not maintained and the flow across them has different inlet velocity. As we decrease the size of the model the inlet velocity decreases as the flow rate which the geometry hold is less. The maximum rpm of the turbine increases as the size of the turbine decreases and torque decreases. But the rpm is maximum at some scale i.e 1:3.375 and it decreases and eventually increases as the scale increases.

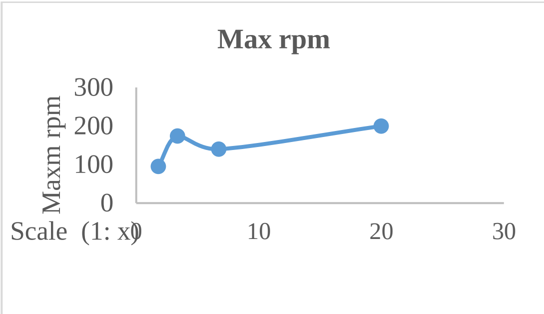


**Figure 9.** Scale vs Maximum rpm

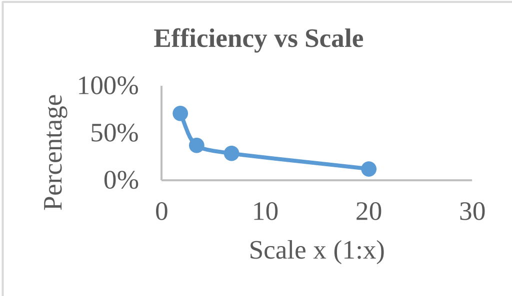


**Figure 8.** Efficiency vs Scale

The turbine efficiency shows the inverse relation with the scaling of the turbine. With the scaling of the turbine, the efficiency decreases. The efficiency is higher in the 1:1.8 scale model and less in the 1:20 scale model. This shows that the turbine efficiency is quite higher than the experimental scale down model.

*5.2. Performance of Generator (Electrical System)*

The major parameters that we should consider while selecting the generator are desired output type (whether we require AC or DC output), Hydraulic turbine operation mode, and the nature of the electrical load (grid connection, storage in batteries or an isolated system). Since this is an isolated micro hydropower system, the major specifications for selection of generator are output power, the number of phases, frequency, current, voltage, the speed of turbine, power factor, excitation type, and so on [18]. Based on these parameters, we have a couple of options to choose the type of generator i.e. either a synchronous generator or an asynchronous generator. Although the asynchronous generator is comparatively cheap and simple in terms of construction of armature, we selected a synchronous generator for our site implementation. The major reason for the selection of synchronous generator is its availability for any capacity, can supply the reactive power without the requirement of the external grid, and the provisions for voltage and power factor regulations [19].

The total power generated by the generator suffers some frictional force at every conversion point. Also, the efficiency of the conversion process is given by:

$$\eta = \eta_{te} * \eta ge * \eta gbe * \eta tre \qquad (10)$$

Where, $\eta$ = total conversion efficiency, $\eta_{te}$ = turbine efficiency, $\eta_{ge}$ = generator efficiency, $\eta_{gbe}$ = gearbox efficiency, and $\eta_{tre}$ = transformer efficiency [20]

The efficiency of the generator used in 3D modeling from both sites is found to be more than 93%. Considering some extra losses that may occur on the system, as mentioned by equation (10), the efficiency of the generator used in real micro-hydro power generation plant will become more than 90%. Thus, the 3D modeling test and the actual generator will correlate with each other and the performance will be similar to the experimental test.

## 6. CONCLUSION

Here, we perform computational and experimental study of a 12-kW turbine through the scale down model of 1:20 scale. This technology has shown high performance operation with a head as low as 1 m. Such hydropower systems are very promising for application in developing countries like Nepal, in particular in the regions where there are strong rivers that flow year-round. We demonstrated different performance of the turbine at various scaling. Compared to existing low-head hydropower technologies, the GWVPP system is still immature and further research is required to optimize the installation but this study using scale down model will help us to understand the real site performance up to certain extend.

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