20th International Conference
ENGINEERING MECHANICS 2014
Svratka, Czech Republic, 12 – 15 May 2014

CONCENTRATION DISTRIBUTION OF COARSE-GRAINED PARTICLE-WATER MIXTURE IN HORIZONTAL PIPE

P. Vlasak[*], Z. Chara[*], J. Konfršt[*], J. Krupička[*]

Abstract: *The paper describes the results of coarse-grained particle-water mixture measurements in an experimental pipeline loop of inner diameter 100 mm. Graded basalt pebbles of mean diameter 11 mm, conveyed by water, were investigated. The concentration distribution measurements were carried out with application of gamma-ray based device. Presented results refer to the effect of mixture velocity and overall concentration on chord-averaged concentration and local concentration distribution in the horizontal pipe. The study revealed that the coarse-grained particle-water mixtures were significantly stratified, solid particles moved principally close to the pipe invert, for higher and moderate flow velocities saltation becomes dominant mode of the sediment transport.*

Keywords: Particle-water mixture; Horizontal conveying; Coarse-grained slurry; Gamma- ray radiometry; Concentration distribution.

1. Introduction

Pipeline transport of coarse-grained material is not very frequently used due to the problems of severe wear, material degradation, high deposition velocity limit and consequently also operational velocities and energy requirement. However, pipeline transport of coarse particles is of potential importance in, e.g. mining industry, the Alberta sands petroleum extraction, or poly-metallic nodules transport from the ocean bottom to the surface (Vlasak and Chara, 2007, Vlasak et al., 2011, 2012). The understanding of the slurry flow behaviour makes it possible to optimize transport parameters and energy requirements, to improve quality, safety, economy and reliability of transport and/or processing of the transported material.

The flow of heterogeneous slurries in a horizontal pipe may be defined as the flow with an asymmetrical concentration and velocity distribution, where a Coulomb friction contributes significantly to the friction losses. A flow pattern with a bed layer and a skewed concentration distribution generally exist for these slurries. The first mechanistic approach for coarse-grained particle slurry flow was probably that of Newitt et al. (1955), who distinguished between velocity dependent fluid friction and velocity independent particle-wall friction of the Coulomb type and defined coarse particle conveyance as flow with a sliding bed and particle saltation.

Wilson (1976) proposed a two-layer model for settling slurries with fully stratified flow pattern, where all particles are supposed to be concentrated in the lower portion of the pipe, where concentration approaches the loose-packed value, and the Coulombic contribution to particle-wall friction is dominant. In the upper layer, only the carrier liquid is presented. Based on experimental data from the large test pipelines of the Saskatchewan Research Council (Gillies et al., 1991) the two-layer model was extended for finer particles. The so called SRC two-layer model is based upon force balance for the upper and lower horizontal layers. All the above mentioned quantities, including the Reynolds number, friction factor and Coulomb type friction are defined for each layer as well as the interfacial friction factor and the flow

[*] Prof. Ing. Pavel Vlasák, DrSc.: Institute of Hydrodynamics ASCR, v. v. i., Pod Patankou 30/5; 166 12, Prague, CZ, vlasak@ih.cas.cz

[*] Assoc. Prof. Ing. Zdeněk Chára, CSc.: Institute of Hydrodynamics ASCR, v. v. i., Pod Patankou 30/5; Prague, CZ, chara@ih.cas.cz

[*] Ing. Jiří Konfršt, PhD.: Institute of Hydrodynamics ASCR, v. v. i., Pod Patankou 30/5; Prague; CZ, konfrst@ih.cas.cz

[*] Ing. Jan Krupička: Institute of Hydrodynamics ASCR, v. v. i., Pod Patankou 30/5; Prague; CZ, krupicka@ih.cas.cz

parameters could be determined (Matousek and Krupicka, 2009). Because the layers differ in the solids concentration and velocity, there is a difference in the mean velocities of the particles and the liquid. Slip between the particles and the liquid results in a continuous transfer of energy from the fluid to the particle and from the particle to the pipe wall.

A progress in the theoretical description of heterogeneous slurry flow is limited due to the lack of experimental data describing the flow behaviour and an inner structure of slurry flow. The study of the inner structure of such flow is very difficult, since many well-known techniques suitable to determine the inner structure of fluid flow (e.g. LDV, PIV, UVP) can be used in solid-liquid mixtures with strong limitations. Description of the slurry flow behaviour and the inner structure are much more complex than measurements of overall flow parameters, e.g. the flow rate, pressure drops, mean concentration.

2. Experimental Equipment and Material

The experimental pipe loop (see Fig. 1) is suitable for study the effect of mixture velocity and concentration on pressure drops in horizontal (A), inclined and vertical (B) pipe sections, which consist of smooth stainless steel pipes of inner diameter D = 100 mm. Slurry was prepared in a mixing tank (1) and pumped into the test loop by a centrifugal slurry pump GIW LCC-M 80-300 (2) with variable speed drive (3) (electric motor Siemens 1LG4283-2AB60-Z A11 with the maximum power of 90 kW). The pressure drops were measured by the Rosemount DP transmitters 1151DP (8) over 2-meter long measuring sections located in the horizontal and the ascending- and descending measuring sections, which are fully inclinable from horizontal to vertical. The mean velocities were measured in a broad range of mean mixture velocities V_s ranged from about 1.5 m/s close to deposition limit velocity ($V_{cr} \approx 1$ m/s), to maximum values about 5.5 m/s by a Krohne magnetic flow meter OPTIFLUX 5000 (9), mounted in the short vertical section (C) at the end of the loop. The vertical U-tube enables evaluation of the delivered concentration of solids. To measure the local concentration the loop is equipped with radiometric density meters (10) and a special support controlled by the computer, which serves for positioning of both the source and the detector. Transparent viewing pipe sections (7) for visual observation were situated just behind the measuring sections in both the horizontal and also in inclinable sections. The flow divider (11) allows collection of slurry samples in the calibrated sampling tank (5) and measuring of the delivered concentration and flow rate.

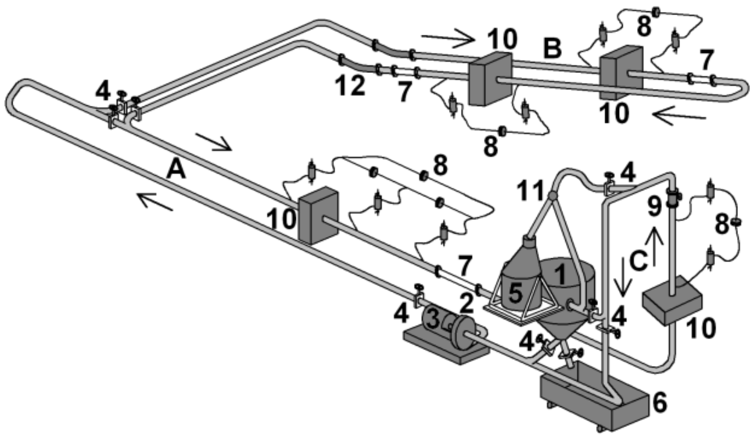


Fig. 1: Experimental test loop.

The loop is equipped with radiometric devices, which make it possible to sense local densities in a pipe cross-section. The radiometric density meters consist of a gamma-ray source (Caesium^{137}Cs, activity 740 MBq) and of a detector (a scintillating crystal of NaI(Tl)). A multi-channel digital analyser enables an evaluation of the energy spectrum of the detected signal. A special support, controlled by the computer, serves for vertical linear positioning both the source and the detector to measure vertical concentration profiles and the concentration distribution through the pipe. The radiometric device was mounted upstream of the measuring and viewing sections in the horizontal part of the loop. A measuring time period of 15 seconds was used to sense the local concentration at each vertical position within a pipe cross section. This time period was found to be sufficiently long to suppress any accidental fluctuations in gamma ray intensity (Krupicka and Matousek, 2012; Vlasak et al., 2014).

The studied mixtures consist of graded basalt pebbles with a narrow particle size distribution (particle diameter, *d*, ranging from 8 to 16 mm, d_{50} = 11.0 mm, density ρ_p = 2 787 kg/m^3), see Fig. 2. Water was used as the carrier liquid and the overall concentration, c_v, ranged from 3 to 15% (Vlasak et al., 2013).

The originally angular basalt gravel quickly degraded and formed a round shape during measurements. The effect of the solid material degradation appears mainly for mixture velocities exceeding 3 m/s and for higher mean concentration values. After short pumping times at higher velocities (above 3.5 m/s), the particle shape and size became practically stabilized, see particle size distribution, Fig. 3. The mean particle diameter changed from the original value d_{50} = 11.7 mm to d_{50} = 11.0 mm (about 94% of the original value),and the mass proportion of particles smaller than 5 mm did not exceed10% even after several hours of pumping.

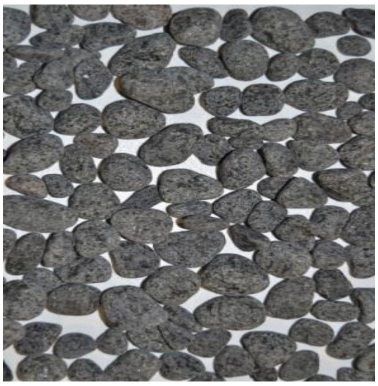


Fig. 2: The used material, graded basalt pebbles.

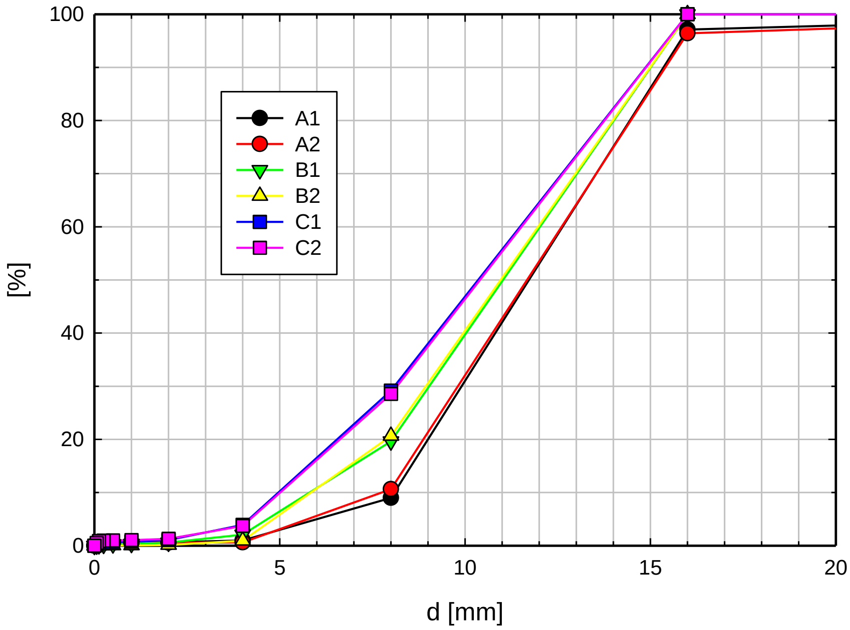


Fig. 3: Particle size distribution of graded basalt pebbles, effect of pumping (A1, A2 – original sample, B1 – after 1.5 hours of pumping, c_v = 5%, B2 – after 4 hours of pumping, c_v = 5%, C1 – after 3 hours of pumping, c_v = 9%, C2 – after 3 hours of pumping, c_v = 14%).

3. Concentration Distribution

Distribution of the local concentration in the pipe cross-section is one of important parameters for understanding the physical mechanism of the heterogeneous mixture flow. It has a great effect on both the mixture's flow behaviour and pressure drop. Various methods have been used for measurement of the local concentration, e.g. isokinetic sampling, visualisation techniques, electrical resistance or radiometric methods.

From visualization of the coarse-grained mixtures flow we found, that particles slid and rolled along the pipe invert for the low mixture velocities. With the increasing mixture velocity individual particles passed to the saltation mode and for higher slurry velocities most of particles lifted off the pipe bottom, moved in saltation or even suspended mode over the whole pipe cross-section. The particle velocities increased with increasing distance from pipe invert; the velocities of the saltating particles were significantly higher than those of the particles sliding or rolling in contact with the pipe wall. For high and moderate flow velocities the particle saltation became very important mode of the particle movement (Vlasak et al, 2012, 2014). However, most of the particles were concentrated in the lover portion of the pipe and moved in saltation mode with intensive rotation and contact with the pipe bottom and walls (Lukerchenko et al, 2006, 2009).

The concentration distribution in the vertical profile of a horizontal pipe section was measured using of a radiometric device and the effects of mixture velocity and concentration on the chord-averaged concentration in the vertical concentration profile were analysed, see Fig. 4. The concentration profile can be divided into two parts. The local concentration tends to approach zero (i.e. practically only the carrier liquid) in the upper portion of the pipe, which occupied from about 35 to 65% of the pipe cross-section; this area increased with decreasing overall mixture concentration.

A nearly linear concentration distribution can be recognized in the lower portion of the pipe. A local maximum concentration could be observed at height about 10 mm from the pipe invert for higher flow velocities. The concentration in the bed layer increased with increasing mean concentration from about 30% to 60%. It was observed that for lower velocities and/or higher means concentrations the bed concentration reached about 60% (value close to the loose-packed value), what demonstrate formation of movable or stationary bed layer.

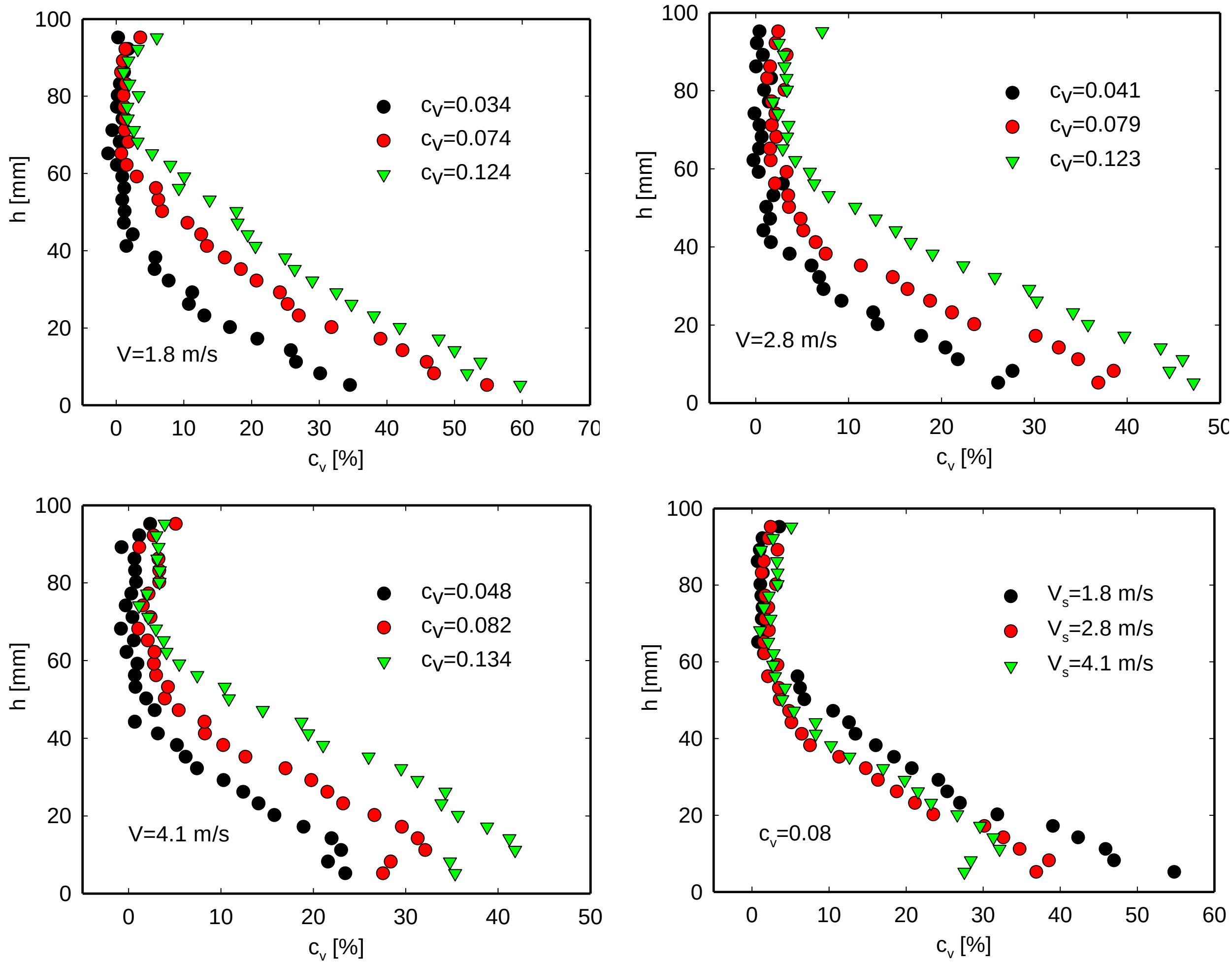


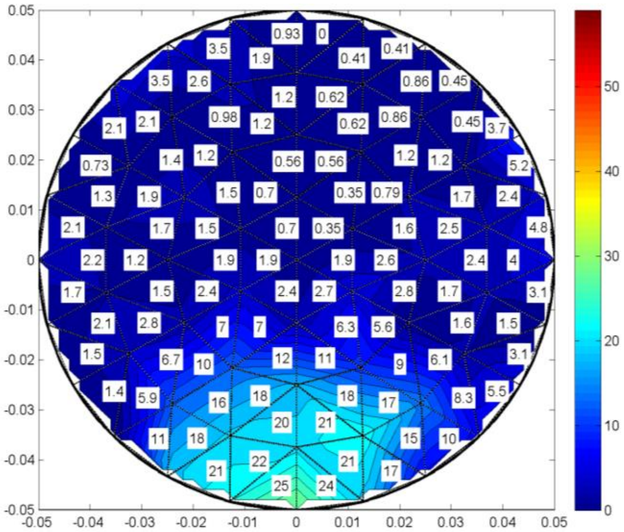
Fig. 4: Vertical profiles of chord-averaged concentration in horizontal pipe.

The observed concentration profiles are in good agreement with the profiles measured by Pugh & Wilson (1999), Matousek (2009), and Sobota et al. (2009) for mixtures of different solid materials with smaller particle diameters. Based on the conducted measurement, it is evident that coarse particles tend to occupy the bottom part of the pipe, but when mixture velocities extended enough the depositions limit, the solid particles commonly moved in the area around the central part of the pipe cross-section.

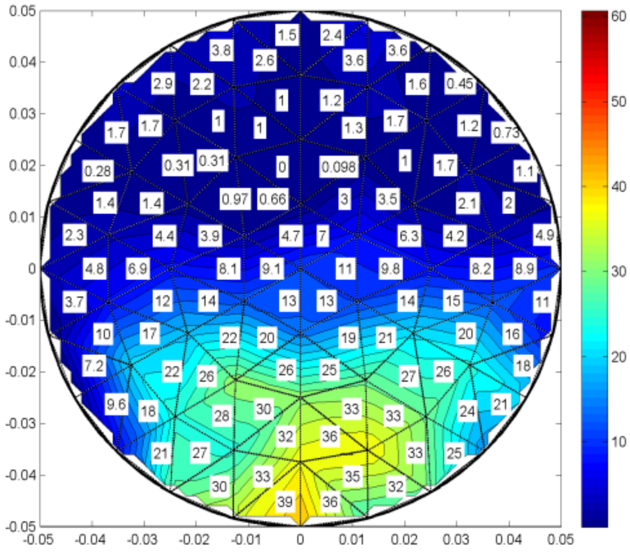
To determine the local concentration distribution through the pipe cross-section the parallel projections of a gamma-ray beams were provided at several angles around the pipe axis (i.e. from 0 to 175° at interval of 15°), and the collected data were processed by the computer tomography method.

Measurement of the local concentration maps is rather time consuming; however it made it possible to evaluate the effect of the slurry velocity, V_s, and mean concentration, c_v, on the solids distribution in the pipe cross-section. From the observed local concentration maps, see Fig. 5, it is evident that conveyed particles tend to occupy the bottom part of the pipe, and their distribution is practically symmetrical to the vertical plane of symmetry.

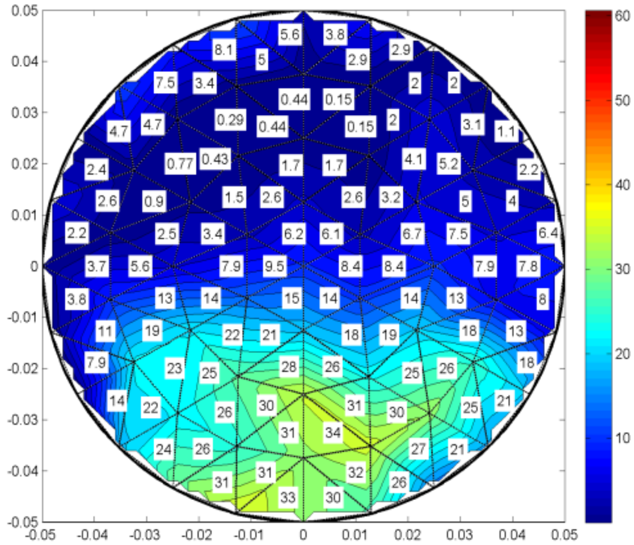
With increasing mixture velocity and concentration values, the measured coarse-grained particles moved commonly in the area above the pipe invert, up to central portion of the pipe cross-section. Particle concentration near both lateral walls of the pipe was observed slightly less than in central portion of the pipe cross-section. The observed particle concentration near both lateral walls of the pipe was slightly less than that in the central portion of the pipe cross-section.



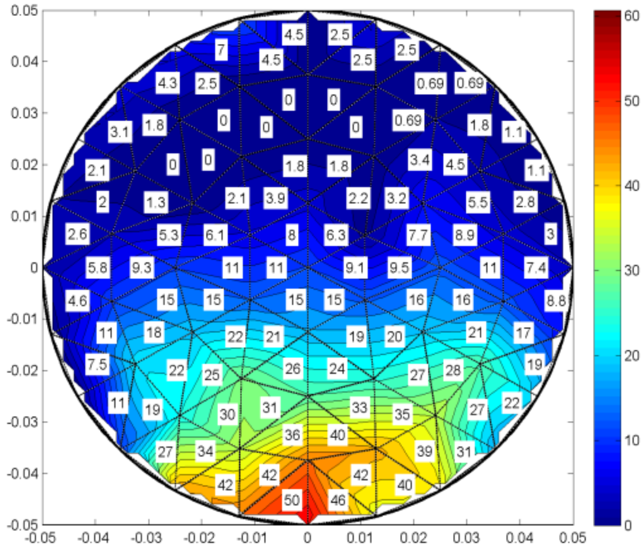
c_v = 5.5 %, V_s =2.8 m/s



c_v = 12.0%, V_s =2.8 m/s



c_v = 12.1%, V_s =3.8 m/s



c_v =13.6%, V_s =2.0 m/s

Fig. 5: Local volumetric concentration distribution in horizontal pipe section.

Particle concentration near both lateral walls of the pipe was observed slightly less than in central portion of the pipe cross-section. The observed particle concentration near both lateral walls of the pipe was slightly less than that in the central portion of the pipe cross-section. The observed concentration maps are in good agreement with the concentration profiles measured for mixtures of different solid materials with smaller particles (Sobota et al., 2009). Some errors were detected in regions close to the pipe wall, and especially near the pipe top, where, probably due to the strong effect of the pipe material on gamma-ray absorption, a higher range of errors was detected (there are no reason for concentration increasing near top of the pipe, especially for lower flow velocities).

4. Conclusions

The effect of slurry velocity and concentration on the flow behaviour of coarse-grained particle – water mixtures' in turbulent regime was studied in horizontal smooth pipe of inner diameter D = 100 mm. The visualisation and local concentration measurements revealed that the coarse-grained particle-water mixtures in the horizontal pipe section were significantly stratified and sliding or even stationary bed layers were formed. The particles moved principally in a layer close to the pipe invert, for higher and moderate flow velocities, particle saltation became the dominant mode of particle movement. Particles were also observed in the central portion of the pipe cross-section.

Measurement of the local concentration distribution in the horizontal pipe confirmed that for coarse-grained mixtures the local concentration tends to approach zero in the upper portion of the pipe (from 35 to 65% of the pipe cross-section). A nearly linear concentration distribution can be recognized in the lower portion of the pipe. The concentration in the bed layer increased with increasing mean concentration, from about 40% to 60%, which is close to the loose-packed value, and it demonstrated flow with sliding bed.

Acknowledgement

Supports under the project P105/10/1574 of the Grant Agency of the Czech Republic, and RVO: 67985874 of the Academy of Sciences of the Czech Republic are gratefully acknowledged.

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