

## GAS BUBBLES AND LIQUID METAL FLOW IN UNIFORM EXTERNAL MAGNETIC FIELD

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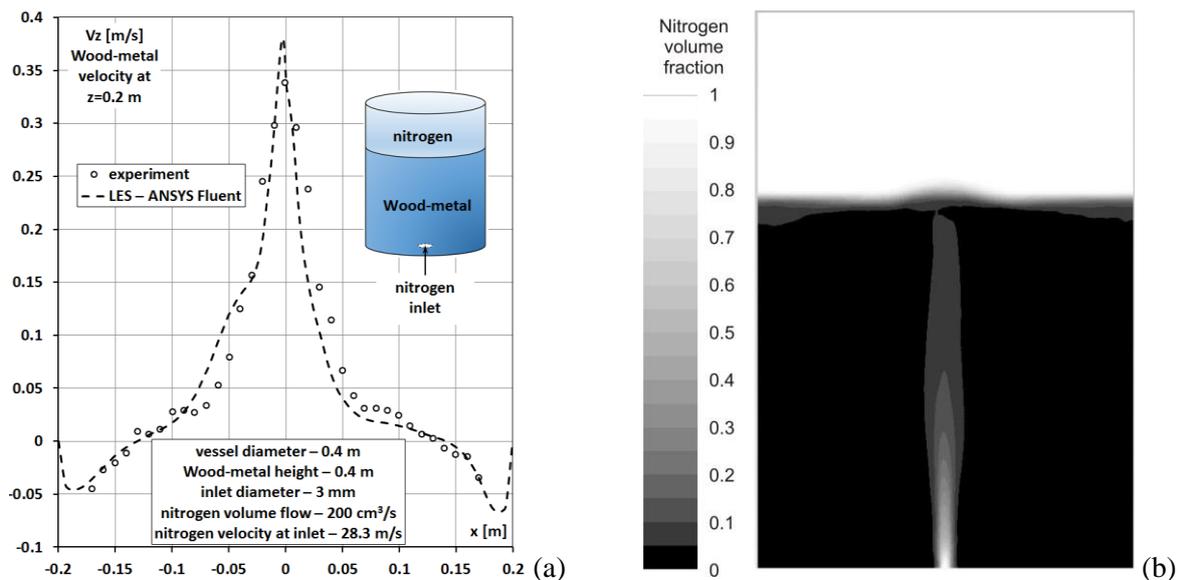
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**Abstract:** The paper presents transient distributions of physical fields, computed with *LES* (*Large Eddy Simulation*), for nitrogen bubbles flow through *Wood-metal* in *cylindrical bubble reactor* (*CBR*), which is placed in external uniform horizontal or vertical magnetic field. Experimentally verified (without magnetic field) *Euler-Euler* approach, realized with *ANSYS Fluent Magnetohydrodynamic (MHD) module*, is used for multiphase flow, when continuous phase is electrically conductive liquid and dispersed phase is gas bubbles.

**Key words:** *Euler-Euler* approach, multiphase *MHD*-flow, *LES*, nitrogen–*Wood-metal* bubble reactor.

### 1. Introduction

With the aim to increase efficiency and to control the process of hydrogen production without generation of carbonic acid by means of methane decomposition the magnetic field may be used, which acts on liquid tin, when methane bubbles are flowing in methane–tin *CBR* [1,2]. Previous studies of single bubble dynamics [2,3] and bubbles collective dynamics [4,5] are continued in current paper with analysis of nitrogen bubbles flow through *Wood-metal* in uniform external magnetic field with application of numerical approach [5], which has been verified by comparison with measurements results [6] without magnetic field (Figure 1).



**Figure 1:** Nitrogen–*Wood-metal* *CBR* with “switched off” magnetic field –  $B = 0$ :  
(a) comparison of measured [6] and *LES* computed *Wood-metal* velocity vertical component for horizontal cross-section at height  $z = 0.2$  m for nitrogen velocity at inlet – 28.3 m/s  
(b) *LES* computed time-averaged (flow time  $t = 1–20$  s) contours of nitrogen volume fraction.

Remember, that to get the desired computational results it is necessary to solve five or eight equations accordingly in cases without or with magnetic field [5].

The computations have been performed using structured fine 3D mesh with ~2.8 millions of elements; mesh is almost uniform to horizontal and vertical directions.

To ensure the stability of computations for the transient flow regime the time step is chosen in the range 0.0001–0.005 *sec*, which corresponds to the *Courant* number value less than the unity. When flow changes in time are extremely fast:

- after the start of gas injection into liquid volume, when *Archimedes* force is prevailing;
- before gas jet, which is flowing in the liquid, joins the gas in the layer above liquid;
- after magnetic field is “switched on”, when *Lorentz* force strongly influences liquid – to gain the stability of computations the time step has been chosen extremely small – up to  $10^{-4}$ ,  $10^{-5}$ ,  $10^{-6}$  or even  $10^{-7}$  *sec*.

As regards to fields’ visualization (Figures 1, 2, 4, 5) there are definite compromises:

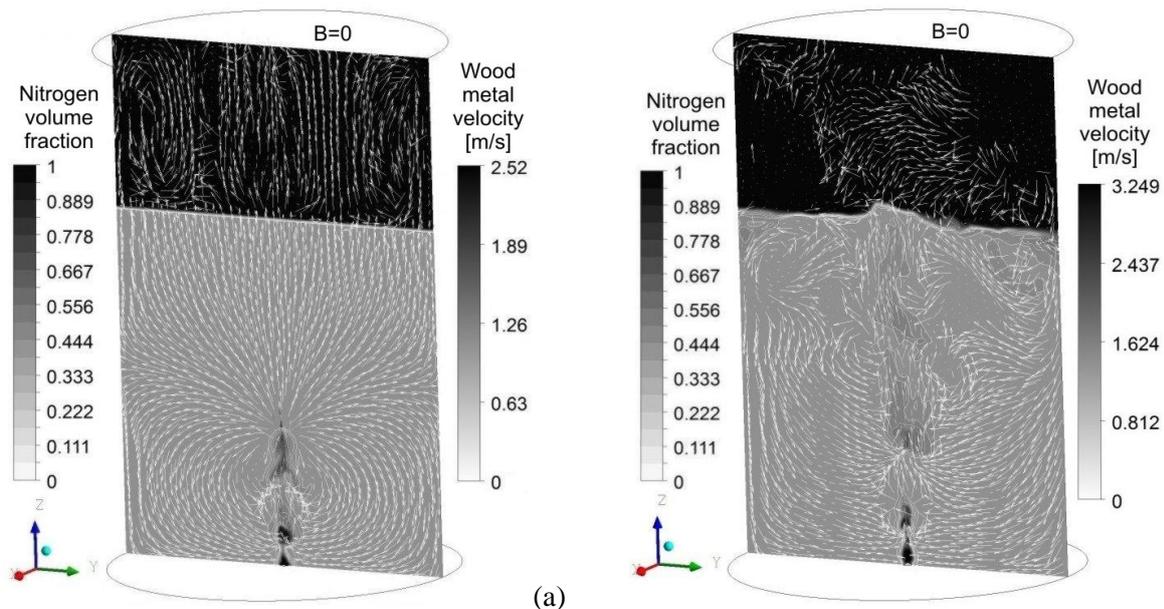
- The plane of cross-section  $x=0$ , which is a little bit rotated around vertical axis for better presentation, has its own grey background, which does not corresponds to grey scale of volume fraction, because nitrogen presence is close to zero in volume except vicinity of jet;
- To gain visualization of flow patterns in the whole volume of liquid but not only near gas jet the velocity vectors are presented with vectors of equal length, but values – in grey scale. Thus light vectors in the liquid present small velocity values, but in the gas layer above liquid the velocity vectors of liquid with values close to zero are visualized as well.

## 2. Absence of magnetic field

For Figures 2, 4, 5 the nitrogen velocity at inlet is 2.58 *m/s* (nitrogen volume flow – 200 *cm<sup>3</sup>/s*; inlet diameter – 10 mm).

In the case, when magnetic field is “switched off”, the jet of nitrogen has the “snake-like” shape from the zone near inlet (Figure 2(a) – flow time  $t = 0.5$  *sec*) to the gas layer above liquid (Figure 2(b) –  $t = 15$  *sec*) – see instantaneous distributions of nitrogen volume fraction.

The *Wood-metal* flow is induced by the jet of nitrogen (the gas velocity in inlet opening is  $v_g^{inlet} = 2.58$  *m/s*). The maximum values of liquid velocity are reached near gas jet.



**Figure 2:** Nitrogen–Wood-metal CBR with “switched off” magnetic field –  $B = 0$ ; cross-sections  $x = 0$ . Instantaneous contours of nitrogen volume fraction and velocity vectors of *Wood-metal* obtained with *LES* model of turbulence for flow time: (a)  $t = 0.5$  *sec*; (b)  $t = 15$  *sec*.

The instantaneous liquid velocity values are permanently changing during the flow time in the range  $v_{l,max}^{inst} \sim 1.9\text{--}4.2\text{ m/s}$  (maximum values are presented at the scales of Figures 2, 4). In the whole volume of liquid, the flow is extremely chaotic, but liquid velocities are approximately for an order smaller as show the light vectors in Figure 2.

The jet of nitrogen reaches the surface of *Wood*-metal approximately in 1.5 sec. After this moment, the surface between nitrogen layer and *Wood*-metal is permanently wave-like. The instantaneous amplitude of surface wave may reach  $\sim 10\text{--}15\%$  of height of nitrogen layer above *Wood*-metal. Time-averaged shape of the wave-like surface may be estimated using time-averaged distribution of nitrogen volume fraction in Figure 1(b).

### 3. Presence of magnetic field

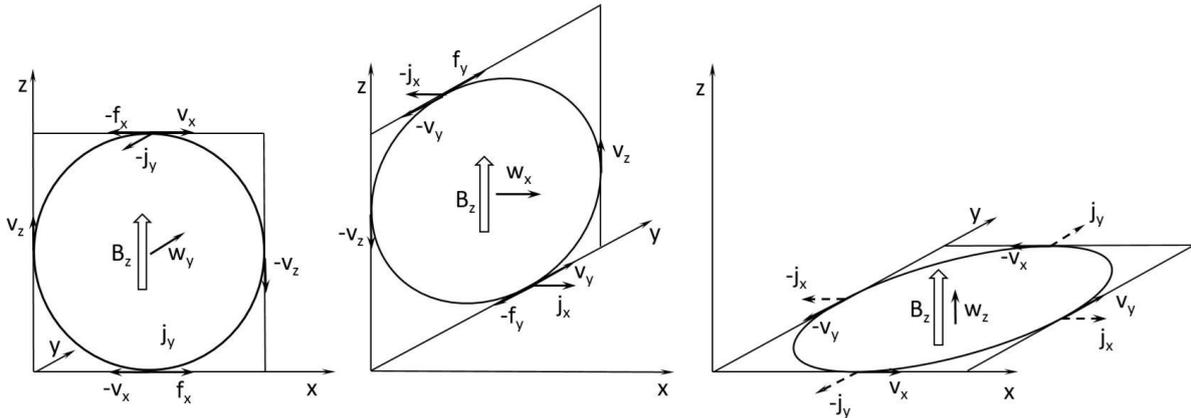
In the case, when external magnetic field is “switched on” the hydrodynamic (HD) interaction of two phases – nitrogen and *Wood*-metal – becomes more complicated due to appearance of *Lorentz* force:

- The velocity of liquid can exceed the greater values if compare with the case with “switched off” magnetic field. The explanation may be as follows.

The flow of electrically conductive liquid in external magnetic field induces *Lorentz* force. The *Lorentz* force breaks the vortices [7, p. 33], which are perpendicular to external magnetic field. The vortices, which are parallel to external magnetic field, are not affected with *Lorentz* force as is shown in the scheme of vector of electromagnetic (EM) and HD fields (Figure 3). If the vectors of velocity vortex and magnetic field are parallel, the electrical current is not induced as shown with dotted lines in Figure 3 (right), because there is not any source of current in the vortex, but the lines of electrical current are closed ( $div \vec{j}_l = 0$ ).

Due to incompressibility of liquid ( $div \vec{v}_l = 0$ ) the spatial distribution of velocity is influenced with the mentioned effect of turbulent vortices breaking by *Lorentz* force.

- The uniform external magnetic field is regularizing the *Wood*-metal flow in reactor, makes it less chaotic and consequently is regularizing nitrogen flow (Figure 4). The nitrogen and *Wood*-metal flows are accelerated in external magnetic field due to breaking effect of *Lorentz* force, which acts to turbulent vortices, and therefore makes smaller the turbulent resistance for nitrogen bubble flow.

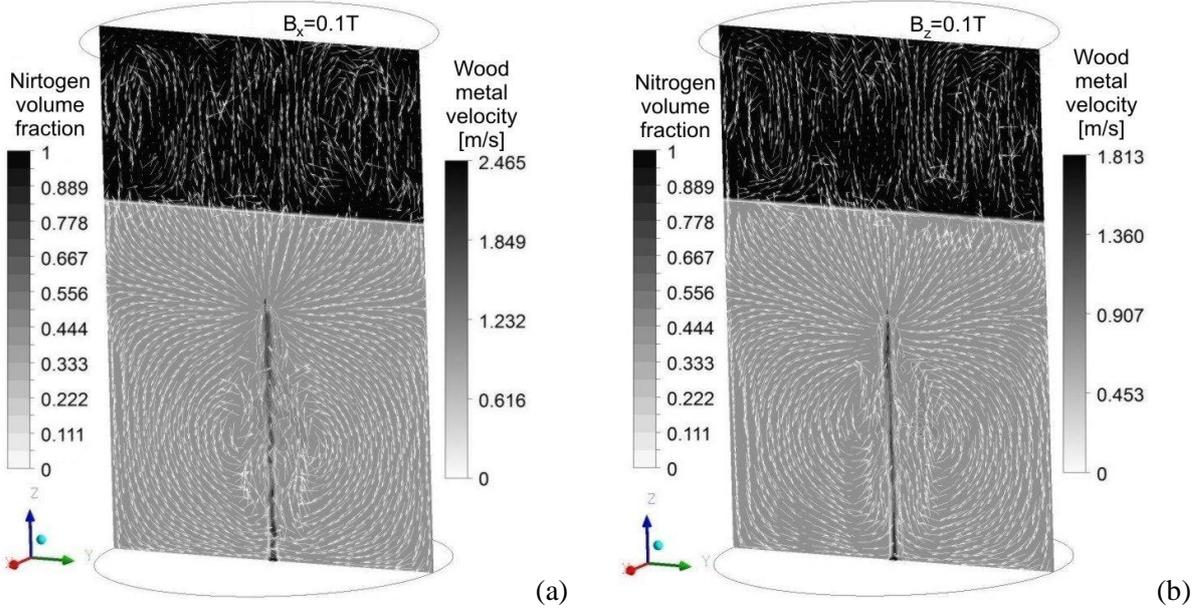


**Figure 3.** The scheme of vector fields in turbulent flow of electrically conductive liquid:

liquid velocity is  $\vec{v}_l = \{v_x, v_y, v_z\}$ ; liquid velocity vortex is  $\vec{w}_l = \{w_x, w_y, w_z\}$ ;

induction of external magnetic field is  $\vec{B}_0 = \{0, 0, B_z\}$ ;

induced electrical current in liquid is  $\vec{j}_l = \{j_x, j_y, j_z\}$ ; *Lorentz* force in liquid is  $\vec{f}_l = \{f_x, f_y, f_z\}$ .



**Figure 4:** Nitrogen–Wood-metal CBR.

Magnetic field is “switched on”: (a) horizontal  $B_x=0.1 T$ ; (b) vertical  $B_z=0.1 T$   
 Obtained with *LES* model of turbulence for flow time  $t = 0.5 s$  the instantaneous contours of nitrogen volume fraction and velocity vectors of Wood-metal for cross-sections  $x = 0$ .

The comparison of Figure 2(a) and Figures 4(a,b) for flow time  $t = 0.5 sec$  – without and with external magnetic field accordingly – shows that the nitrogen jet penetrates into *Wood-metal* approximately two times faster when magnetic field is “switched off”.

At flow time  $t \sim 0.9 sec$  the nitrogen jet reached the top surface of *Wood-metal* and the further jet penetration show *Wood-metal* splash into nitrogen layer – see Figure 5 (a) for flow time  $t = 1 sec$  when vertical external magnetic field is “switched on”. The jet is thin and the maximum instantaneous velocity of *Wood-metal* exceeds the value  $v_{l,max}^{inst} \sim 4.25 m/s$ , which is  $\sim 1.65$  times greater than gas speed in inlet opening  $v_g^{inlet}$ .

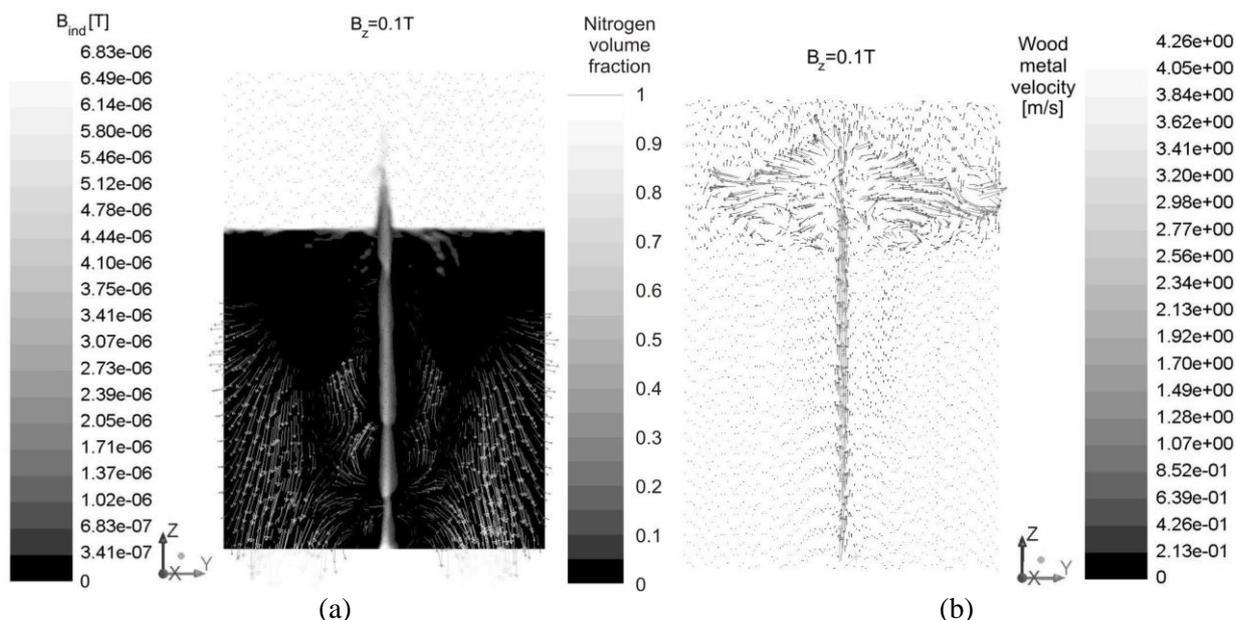
One more validation of developed model presents the estimations of computed instantaneous values of EM field vectors:

- induction of induced magnetic field is  $B_{ind} \sim 10^{-5} T$ , which is for four orders smaller than induction of external magnetic field  $B_0 \sim 10^{-1} T$  – thus the key assumption of developed model is valid –  $\bar{B}_{ind} \ll \bar{B}_0$  – see also Figure 5(a) with induced magnetic field;
- electrical current density ( $\vec{j}_l = rot \bar{B}_{ind} / \mu_0$ ), induced in liquid, is  $j_l \sim 10^3 A/m^2$ ;
- *Lorentz* force density is  $f_l^{EM} \sim 10^2 N/m^3$ , which illustrated, that *Lorentz* force is determined by induced electrical current and external magnetic field  $\vec{f}_l^{EM} = \vec{j}_l \times \bar{B}_0$ .

#### 4. Conclusions

The computations at the fine mesh, which have been performed with application of the developed and experimentally validated 3D model for turbulent gas bubbles and electrically conductive liquid two-phase flow in uniform external magnetic field, make it possible to investigate rapidly developing *MHD*-phenomena of high-speed bubbles injection into liquid metal.

The reason of development of jet-like flow with high maximum velocity is the damping of turbulent vortices in liquid metal by *Lorentz* force and therefore hydrodynamic resistance is damping.



**Figure 5:** Nitrogen–Wood-metal CBR with “switched on” vertical magnetic field  $B_z=0.1$  T. Instantaneous (flow time  $t = 1$  s) distributions obtained with LES model of turbulence: (a) contours of nitrogen volume fraction and vectors of induction of induced magnetic field; (b) velocity vectors of Wood-metal – cross-sections  $x = 0$ .

## 5. Acknowledgments

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