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NUMERICAL SIMULATION OF AN OWC DEVISE

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Abstract. *Wave energy is a renewable and clean energy resource that, in a near future, may become an alternative to the more pollutant fuels. There are a number of wave energy converters prototypes and a few installed text facilities, however there is no device ready for commercial utilization. In this work an Oscillation Water Column Generator (OWC) is numerical simulated using the OpenFOAM software. The VOF (volume of fluid) method is used to solve the multiphase (air + water) fluid flow problem. Regular gravity waves, inside a rectangular (2D) tank, are imposed numerically by prescribing the inlet velocity at the left wall of the tank. The main goal of the work is to simulate the interaction between the generated waves and the OWC device and calculate the energy generated by the turbine (usually a Wells turbine). The air turbine, responsible for the electrical energy generation, is simulated by applying a source (force) term to the momentum equation at the OWC chimney section. Pressure drop at the turbine and air velocity at the chimney outlet section are evaluated as a function of time and used to compute the available energy to be converted into electrical energy. Results are presented and compared for two operating condition: with turbine and without turbine.*

Keywords: *Wave energy, OWC device, OpenFOAM, Numerical simulation, VOF*

1 INTRODUCTION

Power generation is an essential condition for the technological development of a country. Obtaining energy from fossil fuels continues to be an economically viable alternative, however the use of clean and renewable sources is certainly a real possibility that should be explored whenever possible. Brazil has a vast coastline where most of it is suitable for the conversion of wave energy into electrical energy. This natural resource has not been properly used. Not in terms of commercial exploration (there are no commercial plants in operation in the country), neither from the point of view of scientific exploration, since practically only one group at COPPE/UFRJ has been working on building a national device for generating electricity from ocean waves.

There are several types of wave energy converters which can be classified according to their principle of operation as:

i) oscillating water column – OWC;
ii) oscillating bodies (floating body or point absorbers), and
iii) overtopping.

These devices can also be classified according to their distance from the coast as (Cruz and Sarmento (2004)):

i) onshore;
ii) nearshore (located to depths of 20 m), and
iii) offshore (located at depths greater than 20 m).

More detailed information about the technology of energy conversion from sea waves and its current state of development can be found in (Zhang at al., 2009, Falcao, 2010, Bahaj, 2011).

Related to numerical studies of OWC converters, many studies concentrate in improving the device's turbine. Within this context, it is possible to cite the work of Brito-Melo et al. (2002) in which is investigated the influence the aerodynamic design of the turbine wells on the overall performance an OWC. The study also includes the wave climate and the power conversion of an OWC device installed at the Açores island, Portugal. Another example is the work of Falcao (2002) on which speed and power of a Wells turbine coupled to an OWC device was monitored.

More recently, studies of other aspects of the OWC device were published by Marjani et al (2008), Liu et al. (2008) and Conde and Gato (2008). In Marjani et al (2008) it was studied an OWC system similar to the one installed at the island of Pico in Portugal. The model, which include both the chamber and the turbine, concentrates in to analyze the air flow that passed through the chamber and the turbine. FLUENT software has been used to solve a turbulent 3D model.

Liu et al. (2008) presented a computational modeling of an OWC device with different geometries and with different characteristics of waves, including 2D and 3D cases, where it was investigated the water movement inside the OWC device. The Volume of Fluid (VOF) was used to handle the interaction between water and air.

In the research of Conde and Gato (2008) it was analyzed the air flow through an OWC chamber equipped with two chimneys. An one phase model, on which a sinusoidal velocity function is applied at the bottom of the OWC chamber,

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was used to impose the fluid flow inside the chamber. In this model, only the air movement was simulated.

In this paper, a multiphase (air + water) model is used to simulate the water, air, chamber and turbine interactions inside and OWC device. A finite element solution, combined with the VOF method for two inviscid and incompressible fluids, is used to solve the fluid flow problem and determine flow velocities, pressure field and available energy to be converted into electrical energy.

1. MATHEMATICAL FORMULATION

In present solution, the VOF method (Hirt and Nichols, 1981) is used. The VOF is a multiphase model used to solve fluid flow problems with two or more inviscid fluids. In this formulation, all phases are well defined and the volume occupied by one phase can not be occupied by other phases. In the VOF method, a volume fraction for each phase f_i is defined such as:

i) if $f_i \neq 0$ the cell is empty with fluid of phase i;
ii) if $f_i = 0$ the cell is full with fluid of phase i;
iii) if $0 < f_i < 1$ the cell contains the interface between phase i and one or more other fluids.

For the particular case of modeling water and air, only two phases are considered in the formulation.

A single set of momentum and continuity equations is applied to both fluids, and the volume fraction of each fluid in every computational cell (control volume) is tracked throughout the domain by the addition of a transport equation for the volume fraction f. The model is composed by the continuity, volume fraction and momentum equations as follows:

$$\frac{\partial \rho}{\partial t}+\nabla\cdot\left(\rho \vec{V}\right)=0 \tag{1}$$

$$\frac{\partial\left(\rho f\right)}{\partial t}+\nabla\cdot\left(\rho f \vec{V}\right)=0 \tag{2}$$

$$\frac{\partial\left(\rho \vec{V}\right)}{\partial t}+\nabla\cdot\left(\rho \vec{V} \vec{V}\right)=-\nabla p+\nabla\cdot\left(\mu \bar{\bar{\tau}}\right)+\rho \vec{g}+\vec{F} \tag{3}$$

where f is the volume fraction of resin, ρ is the density [kg/m^3], μ the absolute viscosity [Pa s], t the time [s], $\vec{V}$ the velocity vector [m/s], $\vec{g}$ the gravity vector [m/s^2], $\bar{\bar{\tau}}$ the stress tensor [Pa], p the pressure [Pa] and $\vec{F}$ a force (resistance) term [N/m³].

As a single set of momentum and continuity equations is used for both phases, average properties ρ and μ need to be defined. These properties can be approximated as (Srinivasan et al., 2011)

$$\rho=f\,\rho_{water}+\left(1-f\right)\rho_{air} \tag{4}$$

$$\mu=f\,\mu_{water}+\left(1-f\right)\mu_{air} \tag{5}$$

A schematic representation of the computational domain with the used boundary conditions is shown in Fig. 1.

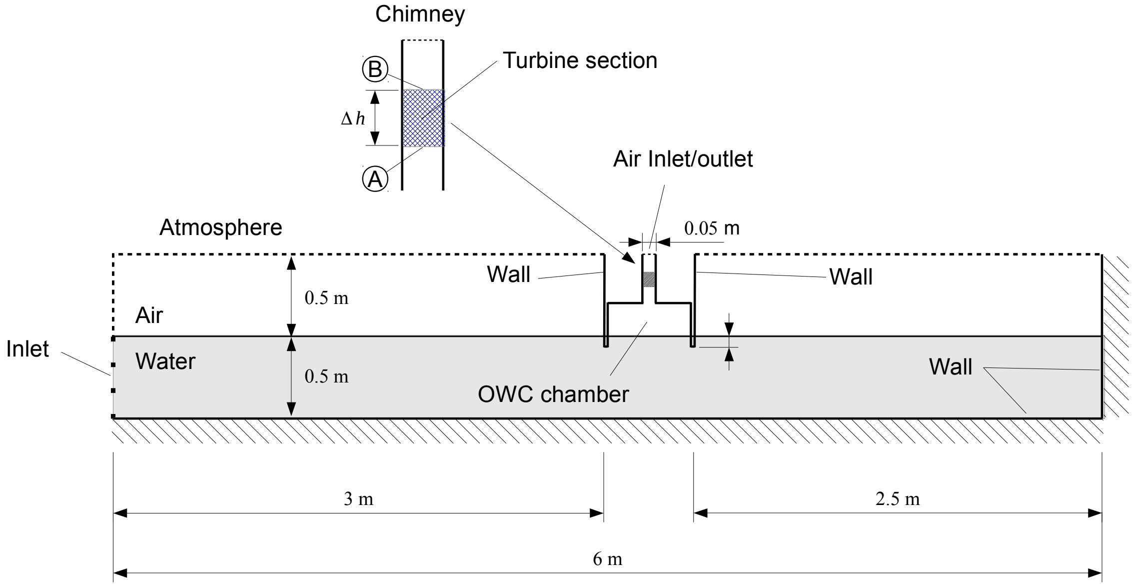

Fig. 1 - Computational domain for the wave tank simulation

In Fig. 1, a rectangular tank with dimension $L \times d$ is initially half-filled with water. The inlet section is defined at the lower part of the left wall (dotted line) where a transient prescribed velocity boundary condition is used to induce

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the wave generation (Eqs. (7) and (8)). The other boundary conditions are: prescribed pressure equal to zero (gauge) at the sections represented with a dashed line in Fig. 1, no-slip condition at the bottom and right walls, chamber walls and chimney walls.

The second order Stokes wave theory, presented by Dean and Dalrymple (1991), is used to evaluate the velocity profile at the inlet section. A schematic representation of the wave with its characteristic parameters is shown in Fig. 2.

In this theory, the free-surface of water (η) is expressed as

$$\eta = A\cos(kx - \omega t) \tag{6}$$

where A is the wave amplitude [m], $k = 2\pi/l$ is the wave number [m^{-1}], $\omega = 2\pi/T$ is the angular frequency [s^{-1}], T the wave period [s], l the wave length [m] and t the time [s].

The velocity in the x and z directions, respectively, are expressed as

$$u = \frac{Agk}{\omega}\frac{\cosh(kz + kh)}{\cosh(kh)}\cos(kx - \omega t) + \frac{3}{4}A^2\omega k\frac{\cosh[2k(h+z)]}{\sinh^4(kh)}\cos[2(kx - \omega t)] \tag{7}$$

$$w = \frac{Agk}{\omega}\frac{senh(kz + kh)}{\cosh(kh)}sen(kx - \omega t) + \frac{3}{4}A^2\omega k\frac{\sinh[2k(h+z)]}{\sinh^4(kh)}\sin[2(kx - \omega t)] \tag{8}$$

where g = 9.81 m/s² is the gravity acceleration.

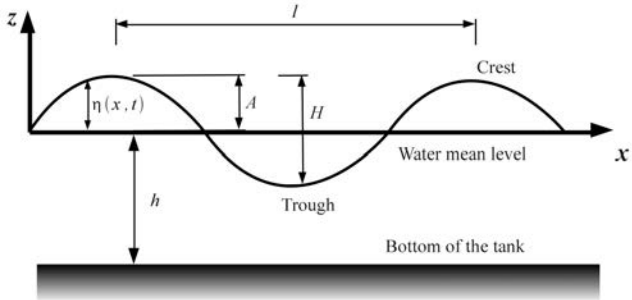

Fig. 2 - Wave characteristic parameters

The problem above described and set by Eqs. (1-8) has already been validated in a previous work (Souza et al., 2012) and for brevity reasons this validation procedure will not be repeated here.

In Fig. 2 is also shown an area called "turbine section". In this area, the turbine effect to the flow dynamics is incorporated to the mathematical model by the inclusion of a porous region.

With the wave (water) movement, the air passing through the chimney is forced in and out of the OWC device. Power is extracted by placing and air turbine at this position. The turbine converts the kinetic energy of the air into electricity. Due to its characteristic of having the rotor blades moving in the same direction no matters the flow direction, Wells Turbines are the usual used within OWC devices.

For a Wells turbine without guide vanes the pressure drop is approximately proportional to the flow rate at constant rotational speed (Sayigh, 2012). Thus, the turbine influence to the flow dynamics can be easy incorporated to the mathematical model by assuming a porous region at the chimney of the the device. The simple porous media model, based on the Darcy's equation states that the pressure drop imposed to a fluid passing through a porous region is proportional to its velocity. In mathematical terms, it can be expressed by

$$\nabla p = -\frac{\mu}{K}\vec{V} \tag{9}$$

where K is the media permeability [m²].

The pressure gradient show in Eq. (9) can be represented by the force term $\vec{F}$ in Eq. (5) where the permeability can be replaced by a constant that correlates pressure gradient and mass flow rate. From a previous work, it was observed that the flow rate passing through the laboratory scale device presented in Fig. 1 varies from zero to approximately 0.005 kg/s (Souza et al., 2012). Assuming the relationship between pressure drop and mass flow showed in Fig. 3 it is possible to write

$$\Delta p = C\dot{m} \tag{10}$$

with C = 50000 Pa/(0.005 kg/s).

Dividing Eq. (10) by Δh, the pressure gradient through the dashed area (detail) in Fig. 1 can be approximated by

$$\nabla P \approx \frac{\Delta p}{\Delta h} = \frac{C\dot{m}}{\Delta h} \tag{11}$$

Combining Eqs. (9) and (13), the pseudo permeability is calculated as

$$K^{-1} = \frac{C\rho A}{\Delta h\mu} \approx 6.15\,x\,10^6 \tag{12}$$

Porous media model is presented in many Computational Fluid Dynamics (CFD) applications. In OpenFoam, the application chosen for the current solution, the porous media model can be easily enabled and the pseudo permeability calculated in Eq. (14) is set without any difficulties.

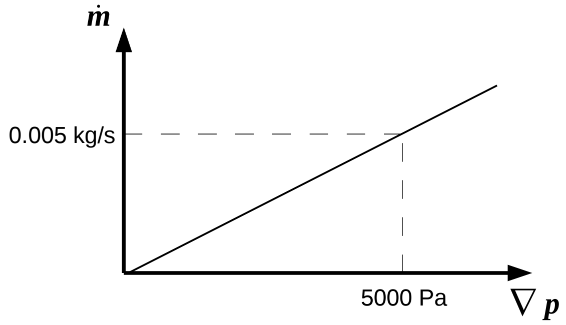

Fig. 3 - Estimated pressure drop to mass flow rate

2 RESULTS

In the current work, the water/air interation with an OWC device is numerically investigated. A simple laboratory scale device is used to investigate the energy produced (available) by the wave (water) movement inside the OWC device. Two cases are investigated and compared:

i) the air can freely flow through the chimney and

ii) a restriction (resistance) is imposed to the air flow passing through the chimney.

The computational domain and boundary conditions shown in Fig. 1 were used in all simulations. Table 1 brings the geometry dimension and wave parameters (see Fig. 2) for the tank and OWC device.

Table 1. Geometry and wave parameters for the OWC simulation

Variable	***L*** **[m]**	***d*** **[m]**	**lip [m]**	***A*** **[m]**	***l*** **[m]**	***h*** **[m]**	***T*** **[s]**
Value	6	1	0.05	0.07	1.2	0.5	0.8

2.1 Flow dynamics imposed by the chimney restriction

Without the turbine, the air is free to flow in and out of the OWC device. The pressure drop imposed to the flow inside the chamber is essentially ruled by the air/water friction with the device's walls and by the section reduction at the chimney's entrance.

With the turbine, a restriction to the air movement is imposed and the flow dynamics is modified, as well as, the pressure and velocity profiles inside the device's chamber. These changes directly influence the available energy at the entrance of the OWC chimney.

The available power is evaluated at the turbine's entrance (section A in Fig. 1) and formulated in terms of static and dynamic pressure as follows

$$P_a=\left(\Delta p+\frac{1}{2}\rho U^2\right)\dot{\forall} \tag{13}$$

where P_a is the available power [W], Δp is the pressure gradient between the sections A and B [Pa], U is the magnitude of the velocity vector [m/s], and $\dot{\forall}$ is the volumetric air flow [m³/s].

The total pressure, defined by the sum of the static, dynamic and hydrostatic pressures as show in Eq. (14) is set equal to zero (gauge) at the outlet section of the chimney. The coordinate system is referenced at the average water level (see Fig. 2) and the outlet section of the chimney is placed at z = 0.45 m.

$$P_t\big|_{z=0.45\text{m}}=p+\frac{1}{2}\rho U^2+\rho g\,\Delta h=0 \tag{14}$$

Assuming constant air density equal to 1.23 kg/m³, the hydrostatic pressure at z = 0.45 m will be kept constant and equal to 5.429 Pa.

In the first instants of the simulation (t < 1s), the water level inside the OWC remains flat (horizontal). During this time U = 0 m/s (dynamic pressure is zero) and the static pressure at sections A and B of the chimney assumes the values of -3.62 Pa (z = 0.3 m) and -4.223 Pa (z = 0.35 m), respectively. According to Eq. (13), even though a pressure gradient exists between the inlet and the outlet sections of the turbine, the power produced is zero since there is no air flow through the turbine.

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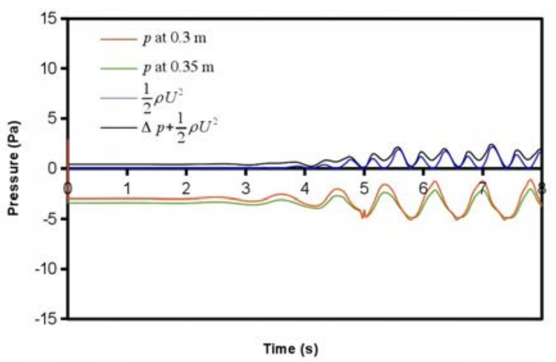
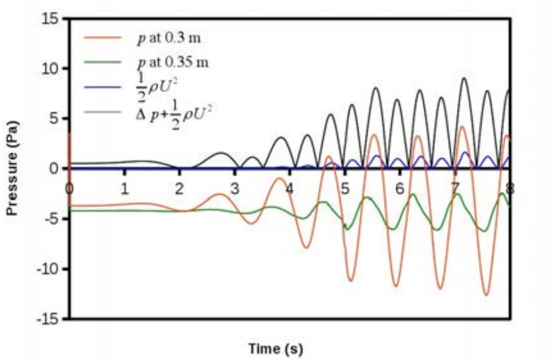
All simulations were performed for t = 1 to 8s (time needed to the wave to reach the right wall of the tank) and results for pressure variation in time are shown in Fig. 4a.

Pressure varies inside the OWC chamber according to the mass flow direction (in and out of the chamber). The turbine, simulated here by a porous zone placed between coordinates z = 0.3 m and 0.5 m, changes the flow dynamics and increases the pressure oscillation amplitude. From Fig. 4a it is possible to observe that static pressure drop $\Delta p = |p_{z=0.3\text{m}} - p_{z=0.35\text{m}}|$, in absolute value, is considerably larger than dynamic pressure and consequently the available power amount is ruled by the first right term in Eq. (13).





(a) (b)

Fig. 4 - Static and dynamic pressure as a function of time: (a) no turbine, and (b) with turbine (K^{-1} = 6.15 x 10^6 m^{-2})

When the turbine (porous media) is removed, pressure drop between sections A and B also diminish. From Eq. (13) it can be observed that the available power to be produced is ruled by the dynamic pressure. Without the turbine, pressure drop in the chimney is only due to the air/walls friction and, as show in Fig. 4b, it is very small in comparison to the dynamic pressure.

In the current small scale experiment, the observed pressure drop is very small and not sufficient to modify the water movement inside the OWC chamber. Thus, the incompressible formulation requires that fluid velocity, and consequently the mass flow rate (see Fig. 5), must be equal for both simulated cases. Since the resistance to the flow is larger when the turbine is present, the pressure inside the OWC chamber must be larger to guarantee the same air velocity. This phenomena can be observed in Fig. 4.

In Fig. 5 it is plotted the mass flow rate through the chimney as a function of time. Positive values indicate that the air is leaving the device and negative values indicate that the air is entering the device.

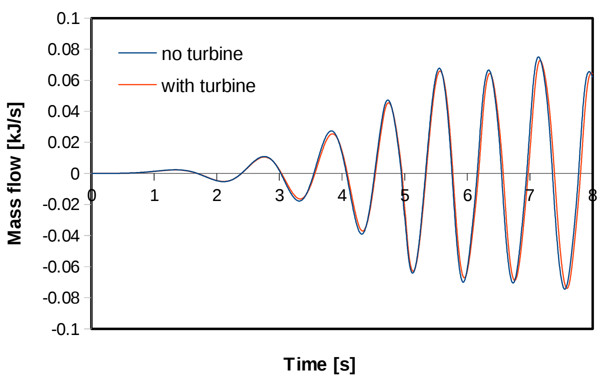


Fig. 5 - Mass flow rate as a function of time

Power can be numerically computed by using Eq. (13) to calculate the instantaneous available energy as a function of time (Fig. 6). If for each time step iteration, Eq. (13) is multiplied by Δt, the instantaneous available energy can be computed. In this sense, the available total power can be calculated by

$$P_a = \frac{\sum_{i}^{N_i} \left[\left(|\Delta p_i| + \frac{1}{2}\rho U_i^2 \right) \dot{\forall}_i \right] \Delta t_i}{t_{total}} \tag{15}$$

where t_{total} is the total simulation time (8s) and index i indicates the integration time step.

The pressure drop in Eq. (15) is taken always positive. Actually it should the calculated as $p_{z=0.3\text{m}} - p_{z=0.35\text{m}}$ when is leaven the chimney and $p_{z=0.35\text{m}} - p_{z=0.3\text{m}}$ when air is entering the chimney.

In Fig. 6, the positive and negative values indicate, in the same way that in Fig. 5., that air is leaving or entering the OWC device, resulting in positive values for energy generated when air is leaving the OWC and negative values when the air is entering the OWC.

Due to the small scale of the OWC, which was chosen like this to simplify the problem and reduce simulation time, the energy produced is extremely small. However, in current study, it is not the amount of produced energy that is being investigated, but if the developed methodology can be used to correctly evaluate energy conversion in a OWC device.

The available power calculated with Eq. (15) was 0.004W for the case without the turbine and 0.009W for the case with turbine.

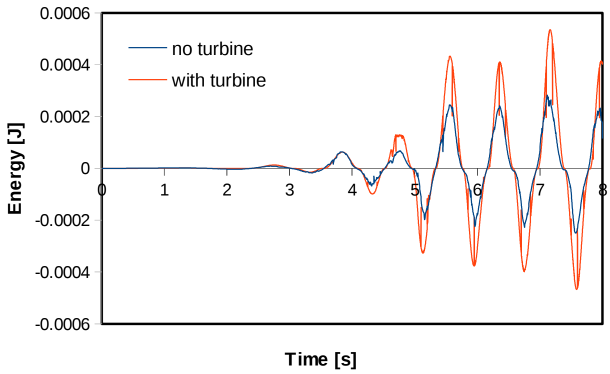


Fig. 6 - Energy available as a function of time

As previously mentioned, due to small dimension considered in this particular study, the pressure drop generated by the inclusion of the turbine at the OWC's chimney is not sufficient to modify the water movement (free-surface) inside the device. In Fig. 7 it is compared the water levels and velocity vectors for the cases with and without turbine (porous media). Comparison is performed for three different simulation times: 5 s, 6 s and 7 s. In all plots of Fig. 7, the vector scale ranges from 0 to 2 m/s. Maximum velocity for each plot is also shown in Fig. 7.

3 CONCLUSIONS

In this work it was presented the numerical simulation of a small scale OWC device. The small size was chosen to simplify the numerical analysis by reducing the number of mesh elements and consequently simulation time. The main goal of the study was to investigate the air/water/device interactions and verify if the used formulation is suitable for determine the wave energy available to be converted into electrical energy.

The proposed numerical model, which uses the VOF method, has been already validated for a simpler problem (wave generation in a rectangular tank) in a previous work (Souza et al., 2012). In this work, the calculated velocity profiles and pressure fields agreed with the expected behavior. However at this point of the research it was not possible to compare obtained results with experimental data. This will be done in a future work with a full scale OWC device.

Transient velocity and pressure fields were calculated inside the OWC chamber and used to evaluate the available energy. Results showed that current solution is suitable for power generation studies in an OWC like devices.

4 ACKNOWLEDGMENTS

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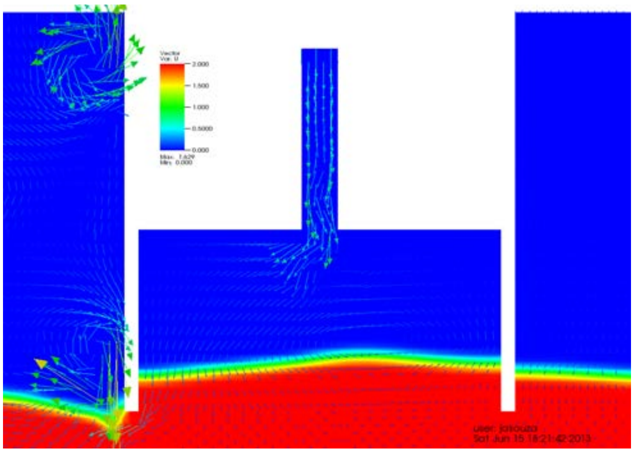
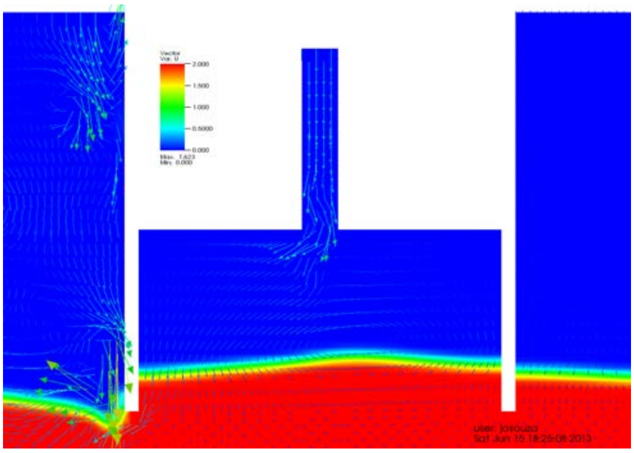
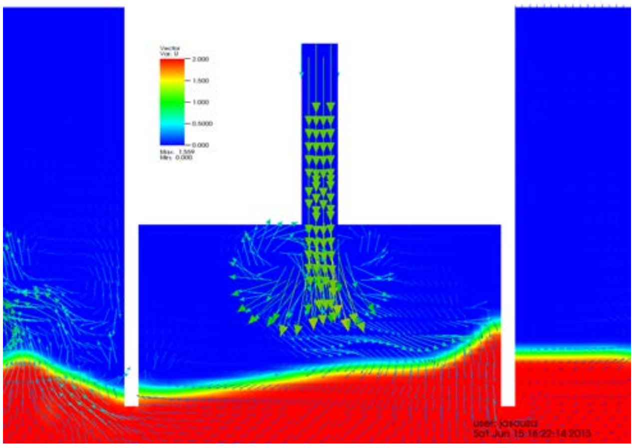


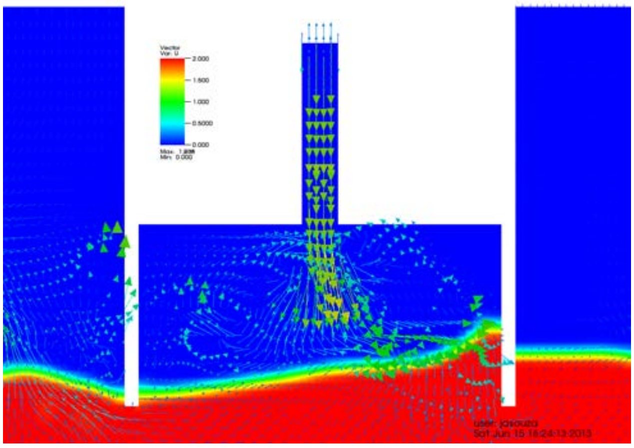
5s – no turbine



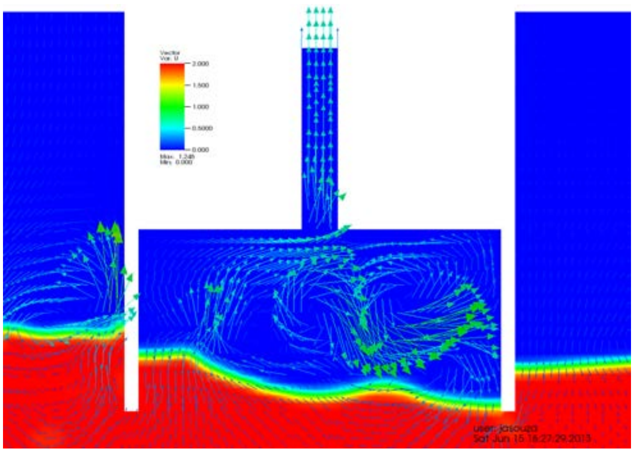
5s – with turbine ($K^{-1} = 1 \times 10^{6}\,m^{-2}$)



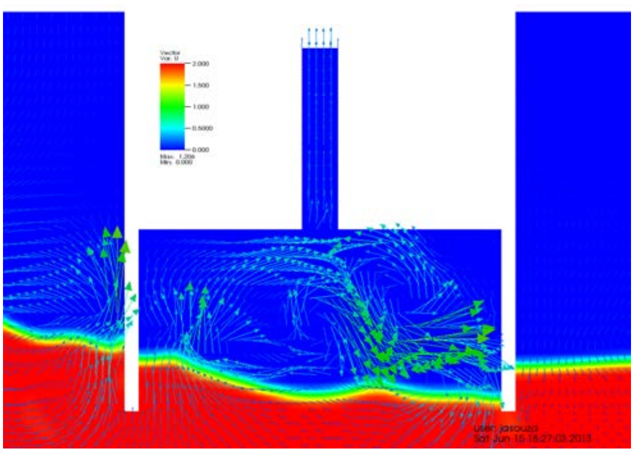
6s – no turbine



6s – with turbine ($K^{-1} = 1 \times 10^{6}\,m^{-2}$)



7s – no turbine



7s – with turbine ($K^{-1} = 1 \times 10^{6}\,m^{-2}$)

Fig. 7 - Water/air interface and velocity fields at 5s, 6s and 7s without (left) and with (right) turbine

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