

Vertical Baffles Height Effect on Liquid Sloshing in an Accelerating Rectangular Tank

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Abstract Sloshing is a phenomenon which still needs considerable understanding in its behaviour related to various engineering problems and is a composition of highly nonlinear waves that may lead to structural damage of the side walls of the container and may destabilize the ship. The aim of this study is to numerically predict the damping effect of baffles on sloshing in tanks partially filled with liquid. The effectiveness and the effect of mounting a baffle vertically just at the free surface on the attenuation of sloshing waves and reduction of the overturning moment were underlined. Commercial software code "FLUENT" is used as a computational platform in this study. Based on the Navier-Stokes equations for viscous, incompressible fluid and Volume of fluid (VOF) method, a two dimensional numerical wave tank is established.

Keywords VOF, Sloshing, Turbulent Flow, Baffles, Tank

1. Introduction

Liquid sloshing in a moving tank constitutes major components in a number of dynamical systems such as aerospace vehicles, road tankers, liquefied natural gas carriers, elevated water towers and petroleum cylindrical tanks. Fluid motion in partially filled tanks can cause large structural loads if the period of tank motion is close to the natural period of fluid inside the tank. The amplitude of the slosh, in general, depends on amplitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry. These parameters have direct effects on the dynamic stability and performance of moving tanks. The baffle inside a tank has been investigated by many researchers and the several recent studies on the effect of baffle on liquid sloshing are summarized as follows. For example Ibrahim et al.[1] analysed the two-dimensional nonlinear sloshing of an incompressible fluid with irrotational flow in a rectangular tank. Sakai et al.[2] investigated the sloshing behavior of floating-roofed oil storage tanks through theoretical analysis and model testing. Kim[3] analysed the sloshing flows with impact load in the two- and three-dimensional containers based on a finite difference method. Mikelis and Journee[4] designed a prototype of the cargo tanks used to transport liquid cargo in ships. They have studied that the integration of pressures around the tank walls yields to overall forces and moments

that are transmitted by the liquids onto the tank structure and consequently on the ship. Chen et al.[5] developed finite-difference method to analyse sloshing in tanks.

Nakayama et al.[6] tackled the problem of sloshing by the boundary element method. They took into consideration the damping effect due to the fluid viscosity by adding an artifice known as the Rayleigh damping term to the condition at the free surface. The control of the sloshing behaviour with baffles is also a subject of interest in the recent years, because of the complexity and highly nonlinear nature of the problem. Some researches carried out the experimental and numerical studies and pointed out the above mentioned characteristics[7-9]. Cho et al.[10] published the results of a resonance analysis of a 2D tank provided with horizontal baffles. With respect to the results of this analysis, it was concluded that the damping effect due to the use of horizontal baffles is significant. Pal and Bhattacharyya[11] carried out the numerical and experimental studies of liquid sloshing for 2D problem. The resulting slosh heights for various excitation frequencies and amplitudes are compared with the data obtained numerically. It was concluded that the little variations in the data are due to the ineptness of the experimental setup and the input parameters. Panigrahy et al.[12] showed experimentally that baffles in a tank decrease the sloshing effect considerably because sharp edged baffles create turbulence in the flow field by dissipating the excess kinetic energy to the walls. Xue and Lin[13] developed a three-dimensional (3-D) numerical model to study viscous liquid sloshing in a tank with internal baffles of different shapes and arrangements. Belakroum et al.[14] predicted the damping effect of baffles on sloshing in tanks partially filled

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with liquid. Chih-Hua et al.[15] used a time-independent finite difference scheme with fictitious cell technique to study viscous fluid sloshing in 2D tanks with baffles. Hakan[16] presented a numerical algorithm based on the volume of fluid (VOF) technique to study the non linear behaviour of liquid sloshing.

According to these studies it appears that the sloshing in tanks is very interesting. For this, the effects of the vertical baffle height on liquid sloshing in an accelerating rectangular tank have been investigated.

2. Geometrical Arrangement

In this paper, a rectangular tank is considered. The geometry is given by the length equal to $b=2$ m and the height equal to $H=3$ m, as shown in Figure 1. The topless tank is partially filled with a fluid height equal to $h=2.5$ m. The height of the baffle h_b is established with the ratio of baffle height to the initial liquid height varying from $h_b/h=0.2$ to $h_b/h=1$. The used fluid is the water where the density $\rho=1000$ kg.m⁻³. The top surface of the fluid is in a state of free surface. The tank is accelerated horizontally with $\gamma=15$ m.s⁻² along a line parallel to two of the walls.

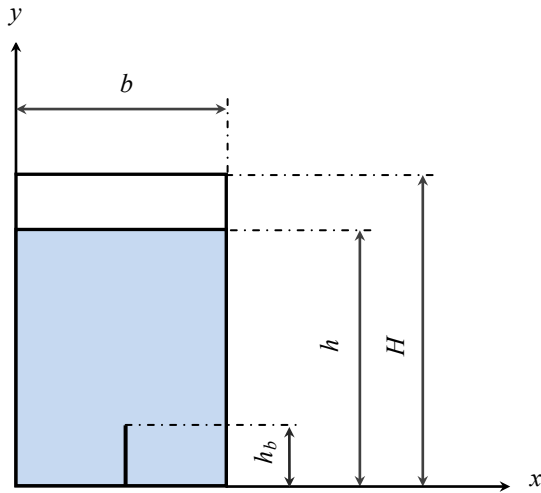


Figure 1. Geometrical arrangement

3. Numerical Model

The commercial CFD code "Fluent" has been used to present the local flow characteristics in the tank. The Navier-Stokes equations in conjunction with the standard $k-\epsilon$ turbulence model were solved using a finite volume discretization method[17-21].

3.1. Mathematical Model

Fluid motion within the fluid is described by the Navier-Stokes equations. This is a set of nonlinear three dimensional partial differential equations.

The first equation describes the conservation of mass:

$$\frac{\partial \rho}{\partial t} = \nabla(\rho v) \quad (1)$$

Where ρ is the density of the fluid and v is the flow velocity vector field in the fluid and (x, y) is the 2D spatial coordinates. This equation is referred to the continuity equation in continuum mechanics. The conservation of mass gives only one equation, but has three unknowns. Therefore, additional conditions are needed, unless the density ρ is known and the problem is one dimensional.

The conservation of momentum Newton's second law of motion gives two more equations.

For a so called Newtonian viscous fluid the conservation of momentum gives the equation:

$$\rho \left(\frac{\partial v}{\partial t} + (v \cdot \nabla) v \right) - (\lambda + \mu) \nabla(\nabla \cdot v) - \lambda \nabla^2 v = -\nabla p + \rho f \quad (2)$$

Where p is the pressure, λ the factor of volume compression, μ the viscosity and f is the external force vector field.

If the fluid is incompressible ($\rho=0$) and inviscid ($\mu=0$), the Navier-Stokes equations become the Euler equations:

$$\nabla \cdot v = 0 \quad (3)$$

$$\frac{\partial v}{\partial t} + (v \cdot \nabla) v = -1/\rho \nabla p + f \quad (4)$$

Inserting the vector identity:

$$\sum (v \cdot \nabla) v = 1/2 \nabla |v|^2 + (\nabla \cdot v) v \quad (5)$$

Assuming that the external force field has a potential:

$$f = -\nabla V \quad (6)$$

Gives:

$$\frac{\partial v}{\partial t} + 1/2 \nabla |v|^2 + (\nabla \cdot v) v = -1/\rho \nabla p - \nabla V \quad (7)$$

3.2. Boundary Conditions

The fluid boundaries in the problem considered are the container walls, bottom and the free surface of the fluid. On the container walls and bottom, the boundary condition is that the velocity of the flow at the wall is zero in the normal direction of the wall.

4. Numerical Results

In this section, we examine numerically how the height of the baffle relative to the initial liquid height affects the liquid sloshing phenomenon when the vertical blade baffle is located at the center of the bottom wall of the tank which is accelerated horizontally with $\gamma=15$ m.s⁻² along a line parallel to two of the walls. Therefore, the main aim of this section is to determine the behavior of the free surface elevation, the velocity fields, the static pressure, the vorticity, the turbulent kinetic energy, the turbulent dissipation rate, and the turbulent viscosity depending on the baffle height. The commercial CFD package "Fluent" is employed for all numerical predictions.

4.1. Free Surface Deformation

Figure 2 presents free surface deformation for different baffle heights equal to $h_b/h=0$, $h_b/h=0.2$, $h_b/h=0.4$, $h_b/h=0.6$, $h_b/h=0.8$ and $h_b/h=1$. When the tank has the baffle with the heights of $h_b/h=0.2$ and $h_b/h=0.4$ among the baffle heights considered in this study, the pattern of liquid sloshing is similar to the case of the unbaffled tank. As the baffle height

increases steadily, the lateral motion of the liquid becomes weaker owing to the augmentation of the blockage effect of the baffle on the liquid convection especially in the region under the baffle. Successively, the free surface behavior becomes stable and the inertial forces are not enough to propel the liquid along the side wall to reach the top wall of the tank. This can be clarified by comparing between the unbaffled tank and the baffled tank with $h_b/h=1$.

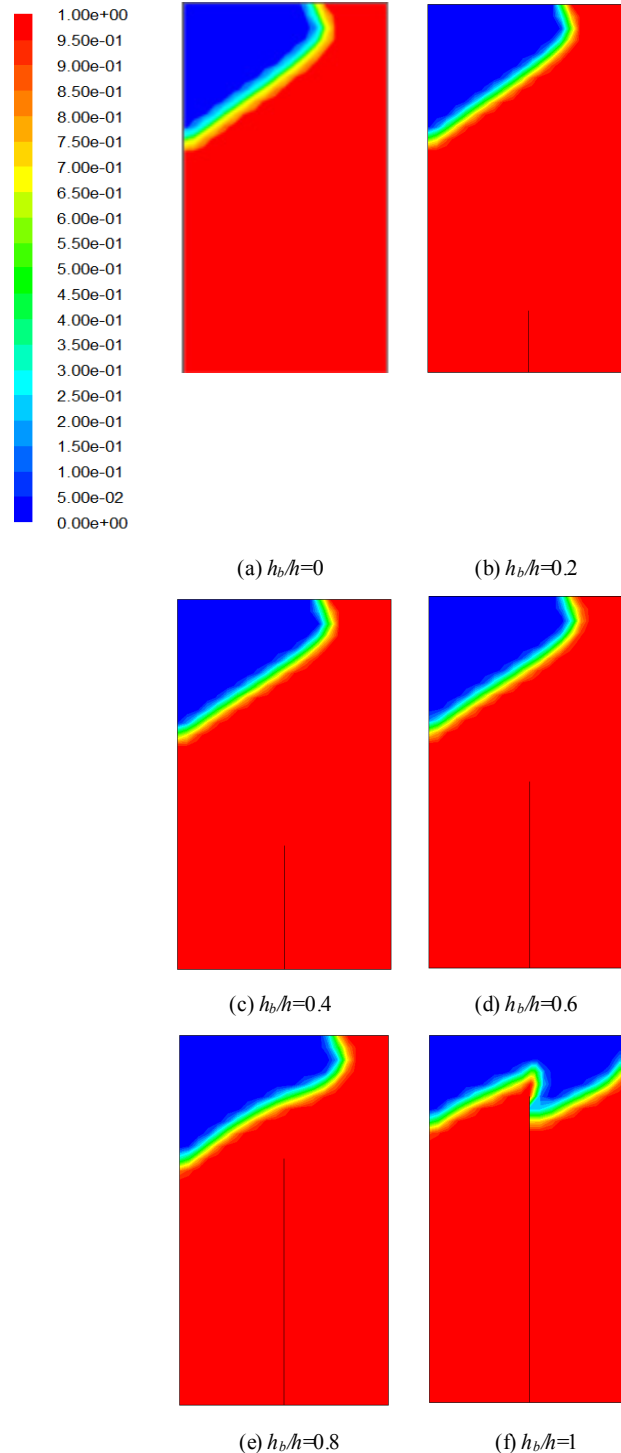


Figure 2. Free surface deformation

4.2. Velocity Fields

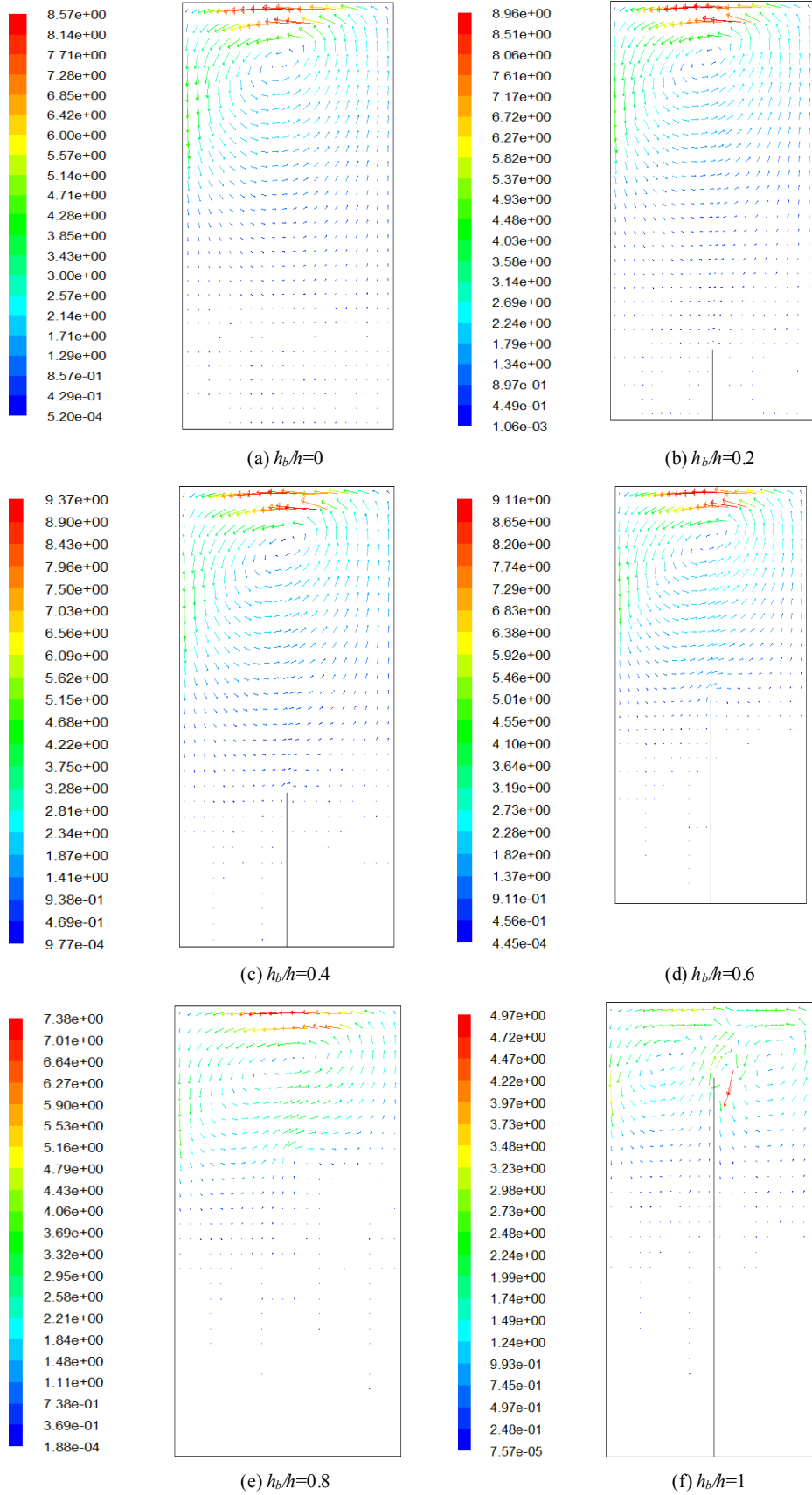
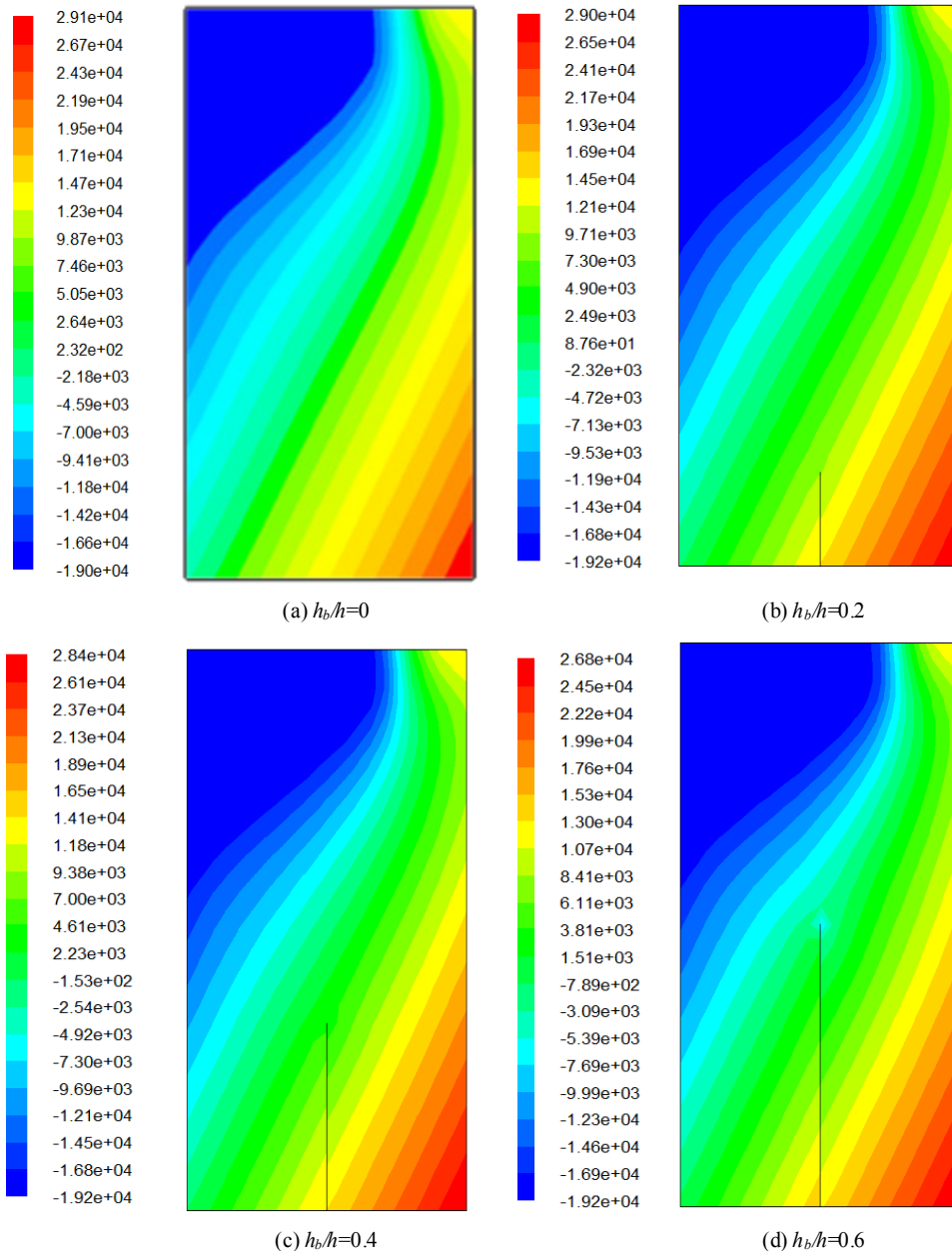


Figure 3. Velocity fields

Figure 3 presents the velocity fields for different baffle heights equal to $h_b/h=0$, $h_b/h=0.2$, $h_b/h=0.4$, $h_b/h=0.6$, $h_b/h=0.8$ and $h_b/h=1$. According to these results, when the considered tank has the baffle with the heights of $h_b/h=0.2$, $h_b/h=0.4$ and $h_b/h=0.6$, we observe an accelerate movement of the flow compared with the case of the unbaffled tank. When the tank has the baffle with the heights of $h_b/h=0.8$ and $h_b/h=1$, a decelerate movement has been observed. The maximum velocity value is obtained for the baffled tank with the height of $h_b/h=0.4$. However the minimum velocity value is obtained for the baffled tank with the height of $h_b/h=1$. A recirculation zone appears in the top of the tank. The extension decreases with the increase of the baffle height. The largest recirculation zone is founded without baffle. However, for the baffle height $h_b/h=1$ it divided in two small recirculation zones.

4.3. Static Pressure

The pressure distribution caused by liquid sloshing at different probes are shown in figure 4 in which the six different baffle heights considered in this study are equal to $h_b/h=0$, $h_b/h=0.2$, $h_b/h=0.4$, $h_b/h=0.6$, $h_b/h=0.8$ and $h_b/h=1$. According to these results, when the tank has the baffle with the heights of $h_b/h=0.2$, $h_b/h=0.4$ and $h_b/h=0.6$ and $h_b/h=0.8$, the compression zones are located at the down right corner of the tank. When the tank has the baffle with the height of $h_b/h=1$, the compression zone are located in the down right corner of the tank and in the baffle down. As the baffle height increases steadily, the value of the static pressure near to the baffle increases.



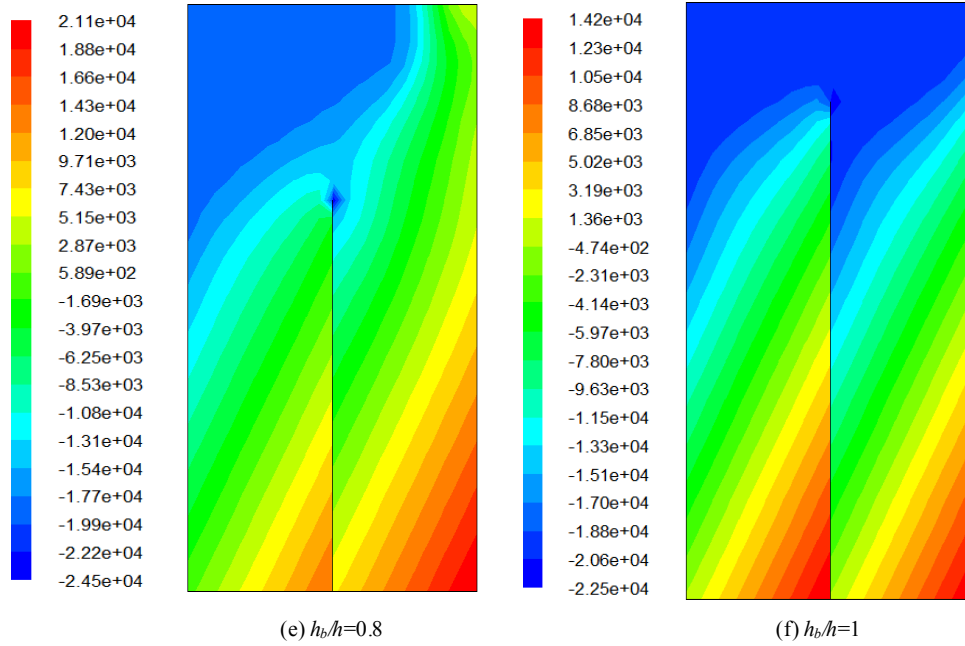
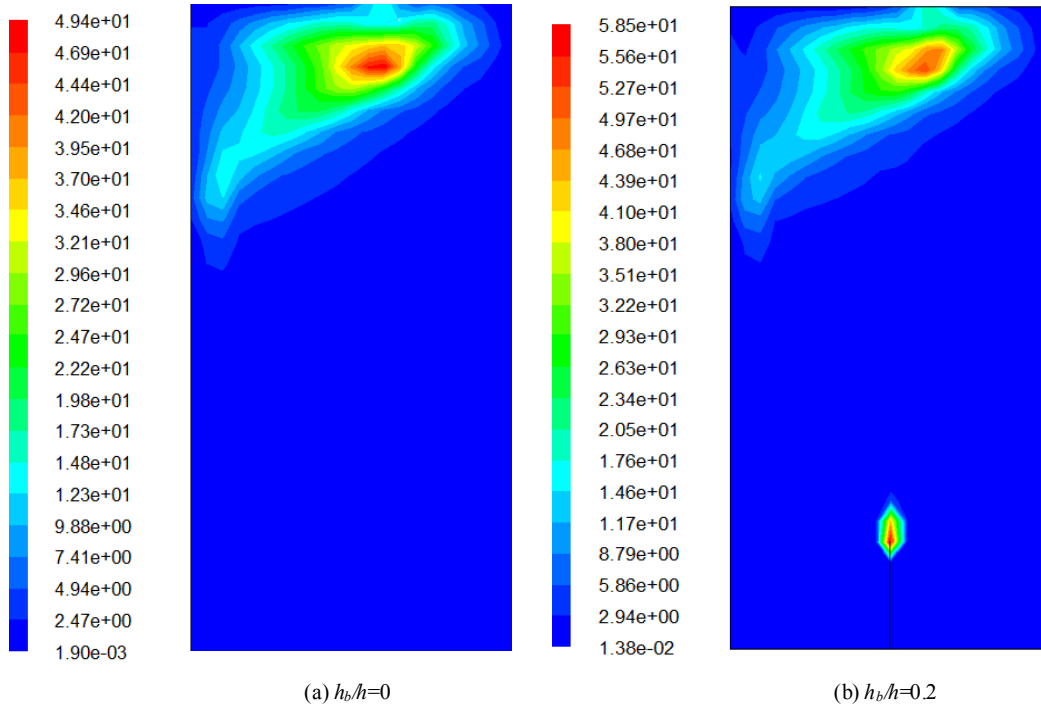


Figure 4. Distribution of static pressure

4.4. Vorticity

The distribution of the vorticity caused by liquid sloshing at different probes are shown in figure 5 in which the six different baffle heights considered in this study are equal to $h_b/h=0$, $h_b/h=0.2$, $h_b/h=0.4$, $h_b/h=0.6$, $h_b/h=0.8$ and $h_b/h=1$. For the unbaffled tank, the highest value of vorticity is located at the free surface. However, with the different considered baffle heights, the highest value of vorticity is located at the free surface and above of the baffle. For the baffle heights equal to $h_b/h=0.2$, $h_b/h=0.4$ and $h_b/h=0.6$, the vorticity value increases with the increase of the baffle height. The maximum vorticity value has been observed for the baffled tank with the height of $h_b/h=0.6$ and it is located in the baffle top. However the minimum value has been observed for the baffled tank with the height of $h_b/h=1$ and for the unbaffled tank.



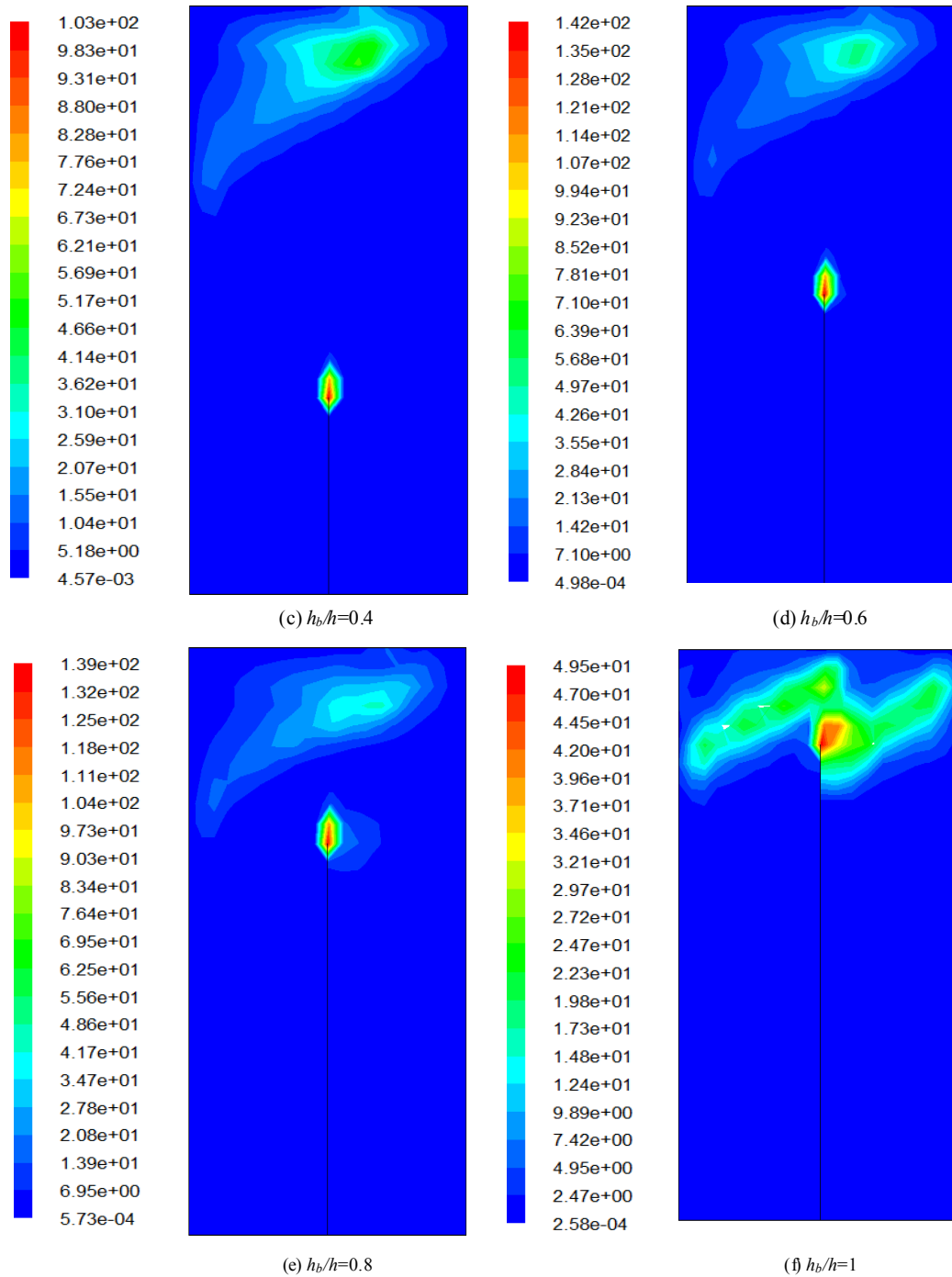


Figure 5. Distribution of vorticity

4.5. Turbulent Kinetic Energy

The distribution of the turbulent kinetic energy caused by liquid sloshing at different probes are shown in figure 6 in which the six different baffle heights considered in this study are equal to $h_b/h=0$, $h_b/h=0.2$, $h_b/h=0.4$, $h_b/h=0.6$, $h_b/h=0.8$ and $h_b/h=1$. According to these results, the turbulent kinetic energy is maximum for the baffled tank with the height of $h_b/h=0.4$ and it is minimum for the baffled tank with the height of $h_b/h=1$. When the tank has the baffle with the height of $h_b/h=0.2$, $h_b/h=0.4$ and $h_b/h=0.6$ among the baffle heights considered in this study, the turbulent kinetic energy is greater than the unbaffled tank. However for the baffle height equal to $h_b/h=0.8$ and $h_b/h=1$, the turbulent kinetic energy is lower than the unbaffled tank.

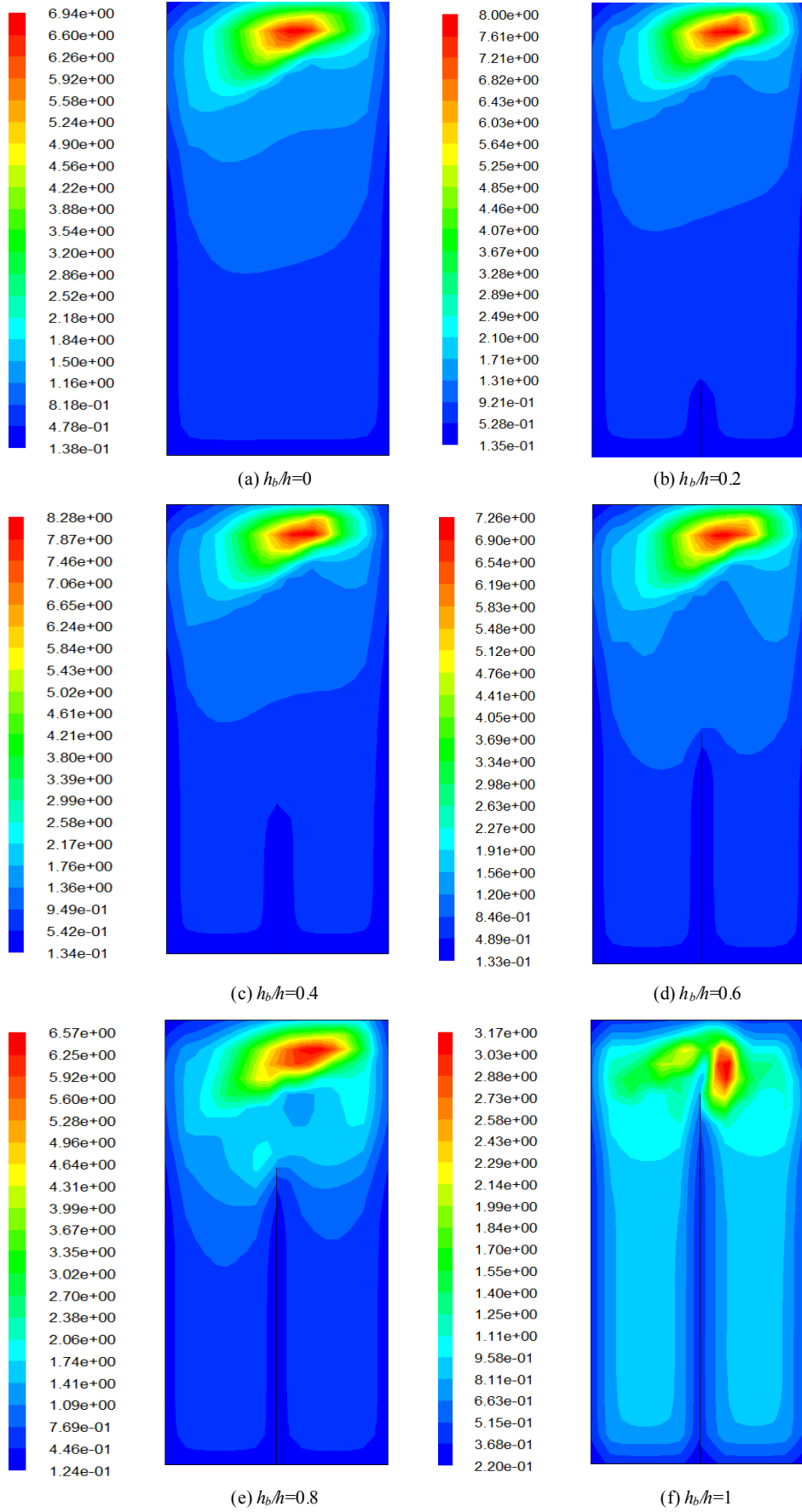
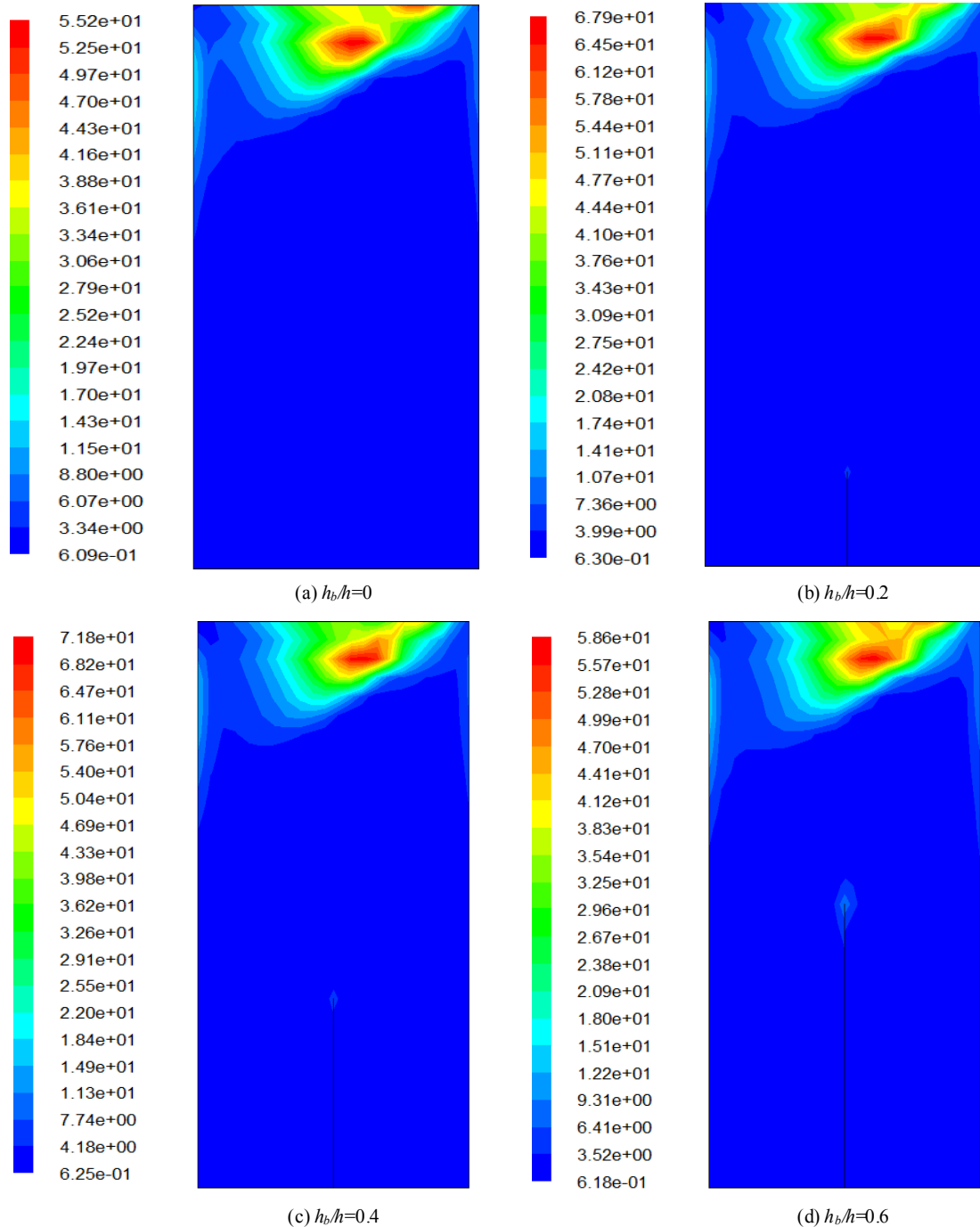


Figure 6. Distribution of the turbulent kinetic energy

4.6. Dissipation Rate of the Turbulent Kinetic Energy

The distribution of the dissipation rate of the turbulent kinetic energy caused by liquid sloshing at different probes are shown in figure 7 in which the six different baffle heights considered in this study are equal to $h_b/h=0$, $h_b/h=0.2$, $h_b/h=0.4$, $h_b/h=0.6$, $h_b/h=0.8$ and $h_b/h=1$. According to these results, the dissipation rate of the turbulent kinetic energy is maximum for the baffled tank with the height $h_b/h=0.4$ and it is minimum for the baffled tank with the height of $h_b/h=1$. When the tank has the baffle height equal to $h_b/h=0.2$, $h_b/h=0.4$ and $h_b/h=0.6$, the turbulent dissipation rate is greater than the unbaffled tank. However, with the baffle height equal to $h_b/h=0.8$ and $h_b/h=1$, the turbulent dissipation rate is lower than the unbaffled tank.



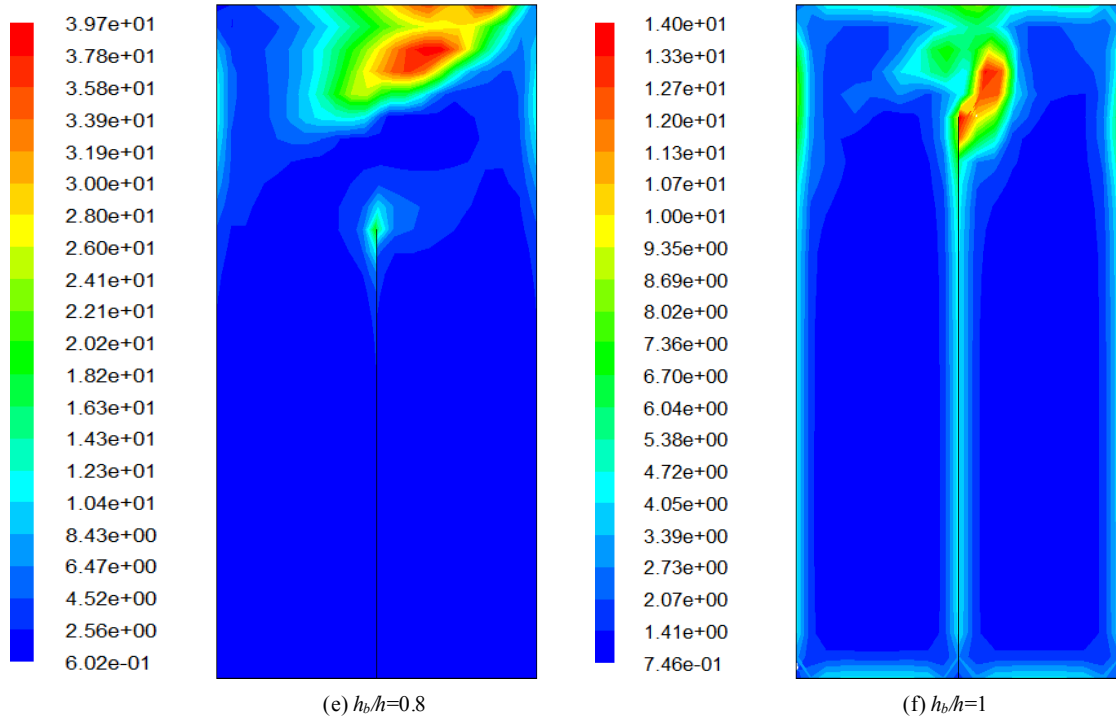
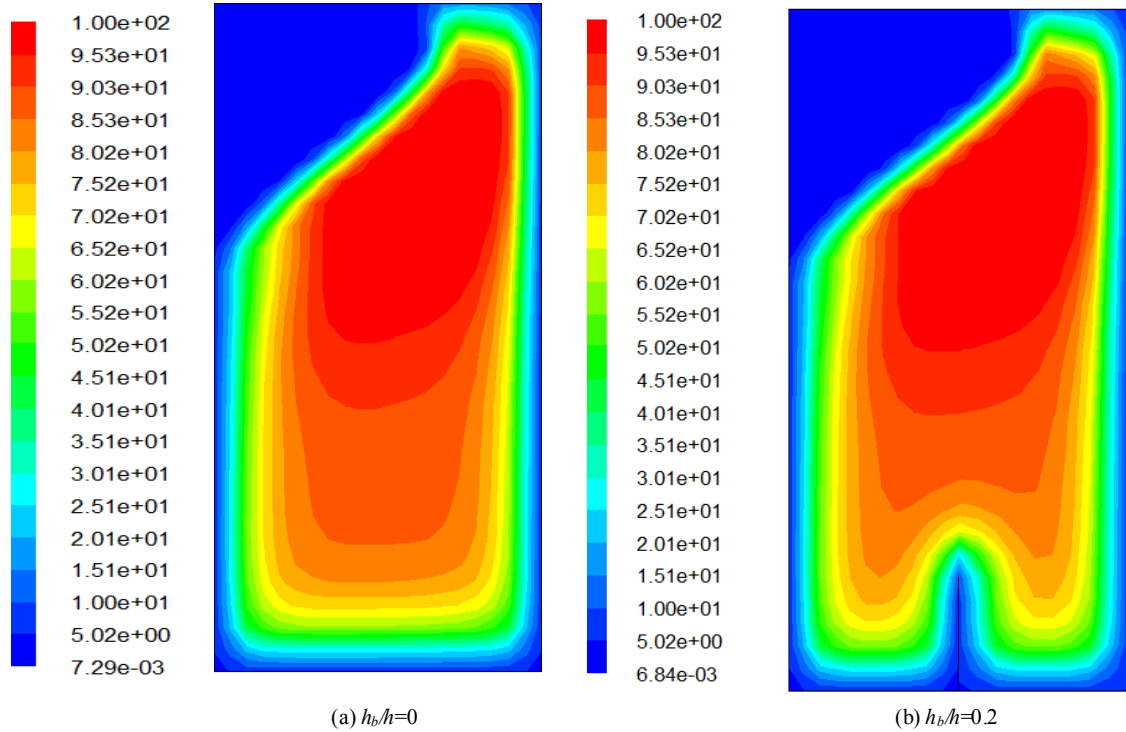


Figure 7. Distribution of the turbulent dissipation rate

4.7. Turbulent Viscosity

The distribution of the turbulent viscosity caused by liquid sloshing at different probes are shown in figure 8 in which the six different baffle heights considered in this study are equal to $h_b/h=0$, $h_b/h=0.2$, $h_b/h=0.4$, $h_b/h=0.6$, $h_b/h=0.8$ and $h_b/h=1$. According to these results, the wake characteristic of the maximum values of the turbulent viscosity appears on the hall volume of water. However, the wake characteristic of the minimum values appears on the areas close to the wall and the baffle.



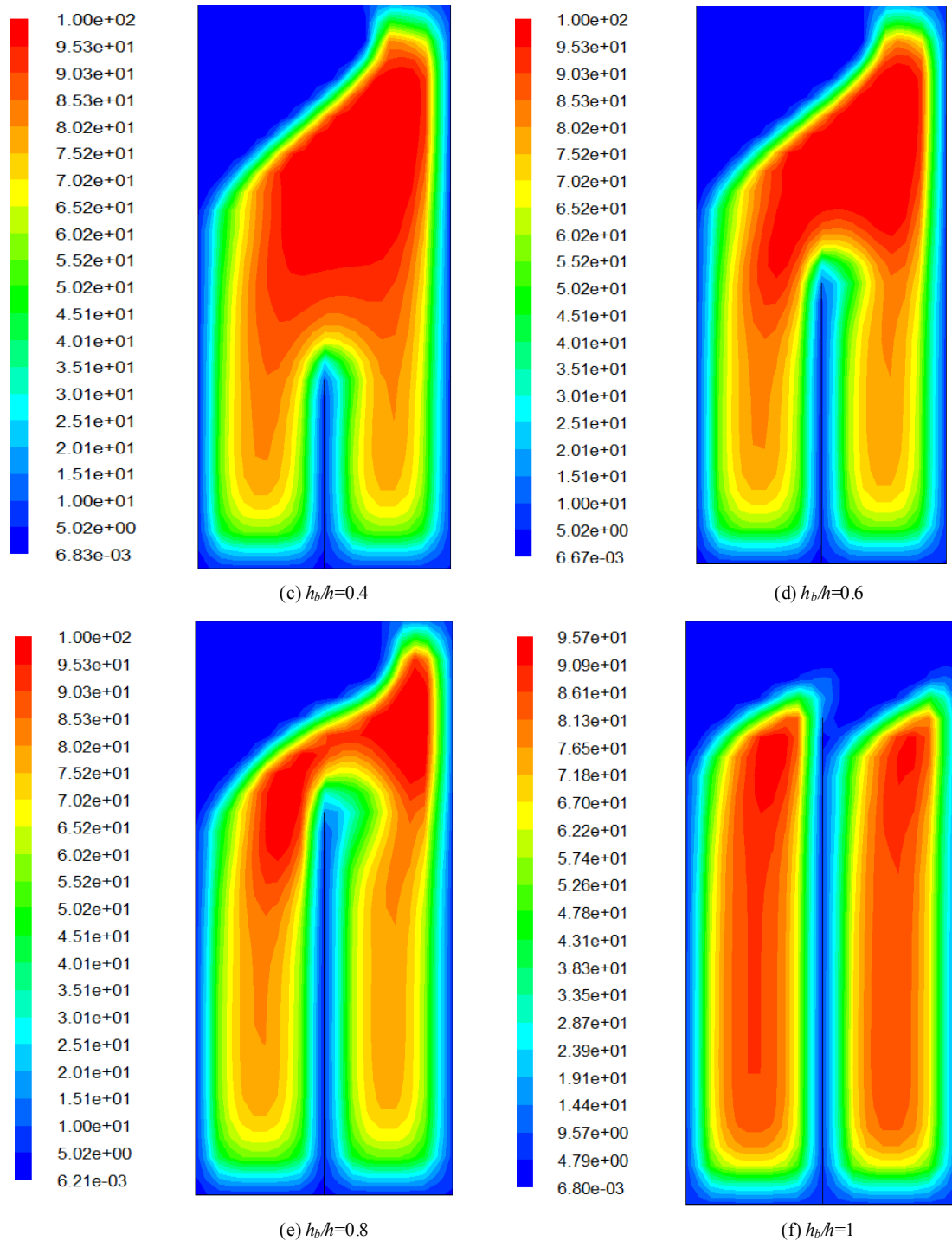


Figure 8. Distribution of turbulent viscosity

5. Conclusions

In this paper, we have studied the effect of a vertical blade baffle on liquid sloshing in a two dimensional rectangular tank by solving two dimensional unsteady incompressible Navier-Stokes equations with the turbulence closure model of the standard $k-\epsilon$ turbulence model. The volume of fluid method has been used to simulate two-phase flow in laterally

moving rectangular unbaffled and baffled tanks. According to this study, we confirm that the baffle height has a direct effect on the hydrodynamic results. In fact, when the baffle height increases, the liquid sloshing becomes more suppressed due to the augmentation of the blockage effect of the baffle, which results in additional viscosity and energy dissipation, also known as hydrodynamic damp.

In the future, we propose to develop a three dimension simulation to study a new tank designs.

Nomenclatures

H	tank height (m)
h	fluid height (m)
h_b	baffle height (m)
b	tank length
v	velocity (m.s^{-1})
γ	acceleration (m.s^{-2})
ρ	density (Kg.m^{-3})
f	external force (N)
p	pressure (Pa)
λ	factor of volume compression
μ	viscosity (Pa.s)
V	potential

REFERENCES

- [1] R.A. Ibrahim, V.N. Pilipchuk, T. Ikeda, "Recent advances in liquid sloshing dynamics", *Applied Mechanical Review*, Vol. 54 (2), pp. 133-199, 2001.
- [2] F. Sakai, M. Nishimura, H. Ogawa, "Sloshing behavior of floating roof oil storage tanks", *Journal of Composites and Structures*, Vol. 19, pp. 183-192, 1984.
- [3] Y. Kim, "Numerical simulation of sloshing flows with impact load", *Applied Ocean Research*, Vol. 23, pp. 53-62, 2001.
- [4] N.E. Mikelis, J.M.J. Journee, "Experimental and numerical simulations of sloshing behavior in liquid cargo tanks and its effect on ship motions", *National Conference on Numerical Methods for Transient and Coupled Problems*. Venice, Italy, 1984.
- [5] B. Chen, R. Nokes, Roger, "Time-independent finite difference analysis of fully non-linear and viscous fluid sloshing in a rectangular tank", *Journal of Computational Physics*, Vol. 209, pp. 47-81, 2005.
- [6] T. Nakayama, K. Washizu, "The boundary element method applied to the analysis of two-dimensional nonlinear sloshing problems", 1981.
- [7] V.A. Buzhinskii, "Vortex damping of sloshing in tanks with baffles. *Journal of Applied Mathematics and Mechanics*", Vol. 62, pp. 217-224, 1998.
- [8] J.R. Chee, S.Y. Lee, "Dynamic analysis of baffled fuel-storage tanks using the ALE finite element method", *International Journal for Numerical Methods in Fluids*, Vol. 41, pp. 185-208, 2003.
- [9] H. Akyildiz, E.N. Unal, "Sloshing in a three dimensional rectangular tank: numerical simulation and experimental validation", *Ocean Engineering*, Vol. 33 (16), pp. 2135-2149, 2006.
- [10] J.R. Cho, H.W. Lee, S.Y. Ha, "Finite element analysis of resonant sloshing response in 2D baffled tank", *Journal of Sound and Vibration*, Vol. 288, pp. 829-845, 2005.
- [11] P. Pal, S.K. Bhattacharyya, "Sloshing in partially filled liquid containers-numerical and experimental study for 2-D problems", *Journal of Sound and Vibration*, Vol. 329, pp. 4466-4485, 2010.
- [12] Panigrahy, P.K., Saha, U.K., Maity, "Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks", *Ocean Eng.*, Vol. 36, pp. 213-222, 2009.
- [13] M.A. Xue, P. Lin, "Numerical study of ring baffles effects on reducing violent liquid sloshing", *Computers & Fluids*, Vol. 52, pp. 116-129, 2011.
- [14] R. Belakroum, M. Kadja, T.H. Mai, C. Maalouf, "An efficient passive technique for reducing sloshing in rectangular tank partially filled with liquid", *Mechanics Research Communications*, Vol. 37, pp. 341-346, 2010.
- [15] C.H. Wu, O.M. Faltinsen, B.F. Chen, "Numerical study of liquids sloshing in tanks with baffles by time-independent finite difference and fictitious cell method", *Computers & Fluids*, Vol. 63, pp. 9-26, 2012.
- [16] H. Akyildiz, "A numerical study of the effects of the vertical baffle on liquid sloshing in two dimensional rectangular tanks", *Journal of Sound and Vibration*, Vol. 331, pp. 41-52, 2012.
- [17] M. Ammar, Z. Driss, W. Chtourou, and M. S. Abid, "Effect of the Tank Design on the Flow Pattern Generated with a Pitched Blade Turbine", *International Journal of Mechanics and Applications*, Vol. 2, N. 1, pp. 12-19, 2012.
- [18] S. Karray, Z. Driss, A. Kaffel, H. Kchaou, M. S. Abid, "Fluid-structure interaction in a stirred vessel equipped with the Rushton turbine", *International Journal of Mechanics and Applications*, Vol. 2, N. 6, pp. 129-139, 2012.
- [19] M. Ammar, W. Chtourou, Z. Driss, and M.S. Abid, "Numerical investigation of turbulent flow generated in baffled stirred vessels equipped with three different turbines in one and two-stage system", *Energy*, Vol. 36, Issue 8, pp. 5081-5093, 2011.
- [20] Z. Driss, M.S. Abid, "Use of the Navier-Stokes Equations to Study of the Flow Generated by Turbines Impellers", *Navier-Stokes Equations: Properties, Description and Applications*, Chapter 3, pp. 51-138, 2012.
- [21] Z. Driss, M. Ammar, W. Chtourou, M. S. Abid, "CFD Modelling of Stirred Tanks", *Engineering Applications of Computational Fluid Dynamics*, Vol. 1, Chapter 5, pp. 145-258, 2011.