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Research Article

Effect of Baffles on the Sloshing in Road Tankers Carrying LPG: A Comparative Numerical Study

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This work presents a comparative numerical study of the effect of using baffles, and its design, on the behavior of sloshing in a partially filled road tanker carrying LPG. Navier-Stokes equations and standard k-ε turbulence model are used to simulate fluid movement; the Volume of Fluid (VOF) method is used to track the liquid-gas interface. Velocity distributions, sloshing stabilization times, and contours of turbulent kinetic energy, which are of high importance in choosing the best design of baffles, are shown. The results show sloshing stabilization times of 22 and 21 s for road tankers with cross-shaped (Type I) and X-shaped (Type II) baffles, respectively, finding lower values of turbulent kinetic energy for Type II design, being, therefore, the best design of baffles for damping of sloshing and vehicle control among studied ones.

1. Introduction

The production of liquid fuels is an activity of great importance worldwide, and particularly for the economic development of Mexico. Once the fuel is produced, it is transported to the different regions of the country by freight vehicles known as road tankers, for its storage, distribution, and consumption. In road tankers filling level is not complete, as indicated by international documents related with transportation of dangerous materials [1], in order to minimize risks and maintain internal pressure below safe limits.

Nowadays, available studies to Mexican companies providing information for the design and manufacture of road tankers are limited, and they usually do not consider the study of the behavior of the fluid within them, despising the effects of sloshing induced by vehicle motion, which is a consequence of changes in direction and speed experienced by road tankers while carrying the fuel. In turn, the sloshing generates dynamic forces that influence the behavior of the vehicle and can alter its stability. To prevent the free movement of fluid and minimize the sloshing, mainly in the longitudinal direction, internal barriers called baffles are used.

In Mexico the common road tankers design includes cross-shaped (Type I), "+," and X-shaped (Type II), "X," baffles, which partially divide the internal space of the tankers in approximately equal size compartment. However, the effect of these baffles' shape on the sloshing has not been formally studied, and reported studies with reliable and relevant technical information have not been found which can lead to the establishment of an appropriate method of selection of the number and shape of baffles, looking for a more effective damping of sloshing.

There are several papers showing numerical simulations on sloshing when using baffles [2–10]. Thundil Karuppa Raj et al. [2] simulated a fuel tank of a car, reporting that the height and location of one baffle are important parameters to decrease sloshing. Some papers show simulations on laboratory scale tanks: Akyildiz [3] studied the effect of the height of a vertical baffle on wave height, the liquid

pressure on the walls, and the velocity distributions in a rectangular tank; Xue et al. [4] studied the effect of a baffle design combining horizontal and vertical baffles with holes of different sizes in a cubic tank and found that the design of the proposed baffle decreases sloshing in the tank.

There are also papers related to ellipsoidal cross section tanks, similar to that studied in the present work. Brar and Singh [5] simulated the behavior of a fluid in a 1 : 3 scale tank with a 2D approximation and show curves of pressure on the walls of the tank when baffles are placed in vertical and horizontal positions inside of the tank, while Domagala et al. [6, 7] simulated the fluid-structure interaction for a two plates-shaped baffles' array dividing a road tanker in three compartments, showing contours of pressure on the tanker wall and on the baffles [6], as well as curves of total force on the tanker structure [7].

There are also studies on road tankers with cylindrical cross section, as the one studied in this work. Zheng et al. [8] simulated a scale model, showing results of the force on the walls of the tanker due to the longitudinal sloshing, finding that for staggered circular-shaped baffles the shape and angle of placement play an important role in decreasing sloshing. Kang and Liu [9] studied the effect of the position of two baffles placed inside of a road tanker 8.6 m long and 2.254 m internal diameter on the sloshing, simplifying by symmetry the studied system, considering only one of the compartments with one baffle. The baffle design employed in the research is a plate with two openings, one upper and one lower, traverse to the cross section of tanker, allowing the passage of fluid [9]. Their results show that the variation of the area of the upper and lower openings, which is related to the height of the plate, has an effect on the forces in the fluid during tanker braking and turning, as well as on the weight distribution during braking and on the rolling moment during a change of direction of the tanker [9].

An approach that differs from the abovementioned studies is the one published by Duan et al. [11], where the effect of the use of insulated and isothermal baffles on the flow pattern inside a spherical container is studied, showing that the fluid movement is more pronounced when using isothermal baffles than with the insulated ones, due to the extra heat brought to the container.

An important parameter in the study of fluid dynamics that quantifies the magnitude of the stirring of a moving fluid is the turbulent kinetic energy; Thundil Karuppa Raj et al. [2] showed that the turbulent kinetic energy is large for a tank without baffles. In this sense, despite the fact that the standard k-ε turbulence model, or one of its variations, has been widely used [6, 9, 12], the reported values of turbulent kinetic energy for tanks with baffles are limited. Furthermore, simulations have focused on using an air-water mixture as the fluid contained in the tank [2, 4, 6, 8, 10], whereas few studies use other fluids such as air-oil [9] or Argon in gas and liquid phases [7]. To simulate the fluid movement in free surface flows, that is, liquid-gas interface, the VOF model has been widely used and validated [3, 4, 8–10].

This research makes a comparative study using numerical simulation to investigate the behavior of sloshing on a road tanker without baffles and with two different designs of baffles during tanker braking, with gas and liquid LPG phases as work fluids. While most of the work reported study tanks at laboratory scale, in this paper a complete road tanker with full dimensions is simulated, because Rodríguez et al. [12] found that there is a different fluid behavior in laboratory scale tanks compared to that which occurs in tanks with full dimensions used in industry. Also, no simplifications in the computational domain due to symmetry were used because the behavior of sloshing is asymmetrical when a change in direction occurs, whose simulation is one of the goals considered for the future work in the road tankers carrying LPG project. Results of velocity distributions, of turbulent kinetic energy, and of fluid stabilization times are shown.

2. Materials and Methods

The system under consideration consists of a horizontal cylindrical container with circular cross section industrially used to transport LPG. Figure 1 shows a diagram of the system under study with its dimensions, with Type I and Type II baffles; separation distance between baffles is approximately equal in accordance with information from measurements on road tankers in service.

2.1. Assumptions about the System under Study for Fluid Flow Simulations

(i) System under study is three-dimensional.

(ii) Fluid inside tanker consists of two homogeneous phases: liquid and gas.

(iii) Fluid is Newtonian and incompressible.

(iv) Flow is turbulent and is in transient state.

(v) Fluid is maintained at a constant temperature of 15.5°C and remains in thermal equilibrium with the walls of the road tanker and this in turn with the surroundings.

(vi) Road tanker is partially filled (90%) by liquid, at an internal pressure of 12 kg/cm^2.

As a source of motion for the fluid road tanker braking from 100 km/h to rest in a time of 30 s was considered, implying that the fluid slowdown is approximately equal to 1 m/s^2; for calculations an exact value of 1 m/s^2 was used.

The whole phenomenon can be divided into two stages: in the first one momentum is given to the fluid and comprises 30 s (braking time of the road tanker), while the second stage starts after giving momentum to fluid and ends once it is considered that the fluid comes to rest.

Stage I is as follows:

$$\begin{aligned} &0 < t \leq 30, \\ &a_x = 1\ \mathrm{m}^2/\mathrm{s}, \\ &a_y = -9.81\ \mathrm{m}^2/\mathrm{s}. \end{aligned} \tag{1}$$

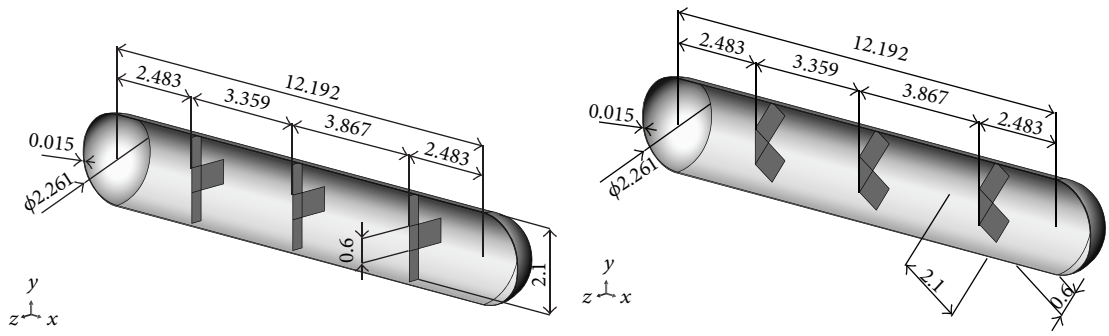

Figure 1: Studied circular cross-section road tanker and its dimensions, with (a) Type I ("+") and (b) Type II ("X") baffles.

Stage II is as follows:

$$t > 30,$$
$$a_x = 0\,\mathrm{m}^2/\mathrm{s}, \tag{2}$$
$$a_y = -9.81\,\mathrm{m}^2/\mathrm{s},$$

where a_x and a_y are fluid acceleration values in x and y direction, respectively.

2.2. Equations Used for the Model. VOF model (Volume of Fluid) was used to simulate the behavior of the liquid-gas interface. VOF model shares a momentum equation for both fluid phases, and volume fraction of each phase is tracked throughout the domain. Involved equations are shown.

Equation for the volume fraction of the liquid phase is as follows:

$$\frac{\partial \alpha_q \rho}{\partial t} + \nabla \cdot \left(\alpha_q \rho \vec{v}\right) = 0, \tag{3}$$

where $\vec{v}$ is the velocity vector of phase q, ρ is fluid density, and α_q represents the volume fraction of the phase, where q takes the value of 1 for the gas phase and 2 for the liquid phase; the equation for the volume fraction of the gas phase is determined by

$$\sum_{q=1}^{n} \alpha_q = 1. \tag{4}$$

Momentum equation is as follows:

$$\frac{\partial}{\partial t}\rho\vec{v} + \nabla \cdot \left(\rho\vec{v}\vec{v}\right) = -\nabla P + \nabla \cdot \left[\mu\left(\nabla\vec{v} + \nabla\vec{v}^T\right)\right] + \rho\vec{g}, \tag{5}$$

where $\vec{g}$ is the gravity vector and μ is the sum of dynamic and turbulent viscosities as shown in (5):

$$\mu = \mu_d + \mu_t. \tag{6}$$

Turbulent viscosity is determined from the standard k-ε model, which is used to represent the turbulence. The density and dynamic viscosity are determined by the following, respectively:

$$\rho = \alpha_2\rho_2 + \left(1 - \alpha_2\right)\rho_1, \tag{7}$$
$$\mu_d = \alpha_2\mu_2 + \left(1 - \alpha_2\right)\mu_1. \tag{8}$$

2.3. Initial and Boundary Conditions

Stage I

Initial Conditions

For: $t_{\mathrm{I}} = 0$, $v_x = 100\,\mathrm{km/h}$, $v_y = v_z = 0$

v_x, v_y, v_z are fluid velocities anywhere in the x, y, z, directions, respectively.

Boundary Conditions

For: $0 < t_{\mathrm{I}} \leq 30\,\mathrm{s}$, $v_{x,W\mathrm{I}} = (100/30)(30 - t)\,\mathrm{km/h}$, $v_{y,W\mathrm{I}} = v_{z,W\mathrm{I}} = 0$

$v_{x,W\mathrm{I}}$, $v_{y,W\mathrm{I}}$, $v_{z,W\mathrm{I}}$ are the magnitude of the fluid velocities in the walls of the road tanker in the x, y, z, directions, respectively.

Stage II

Initial Conditions

For: $t_{\mathrm{II}} = 0$ $(t_{\mathrm{I}} = 30\,\mathrm{s})$, $v = v(x, y, z)$

$v = v(x, y, z)$ is the fluid velocity anywhere in the x, y, z, directions obtained from the velocities field at the end of Stage I.

Boundary Conditions

For: $t_{\mathrm{II}} > 0$ $(t_{\mathrm{I}} > 30\,\mathrm{s})$, $v_{x,W\mathrm{II}} = v_{y,W\mathrm{II}} = v_{z,W\mathrm{II}} = 0$

$v_{x,W\mathrm{II}}$, $v_{y,W\mathrm{II}}$, $v_{z,W\mathrm{II}}$ are the magnitude of the fluid velocities in the walls of the road tanker in the x, y, z, directions, respectively.

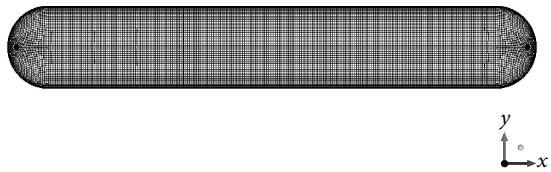

Figure 2: Mesh for the system under study with 305760 hexahedral cells.

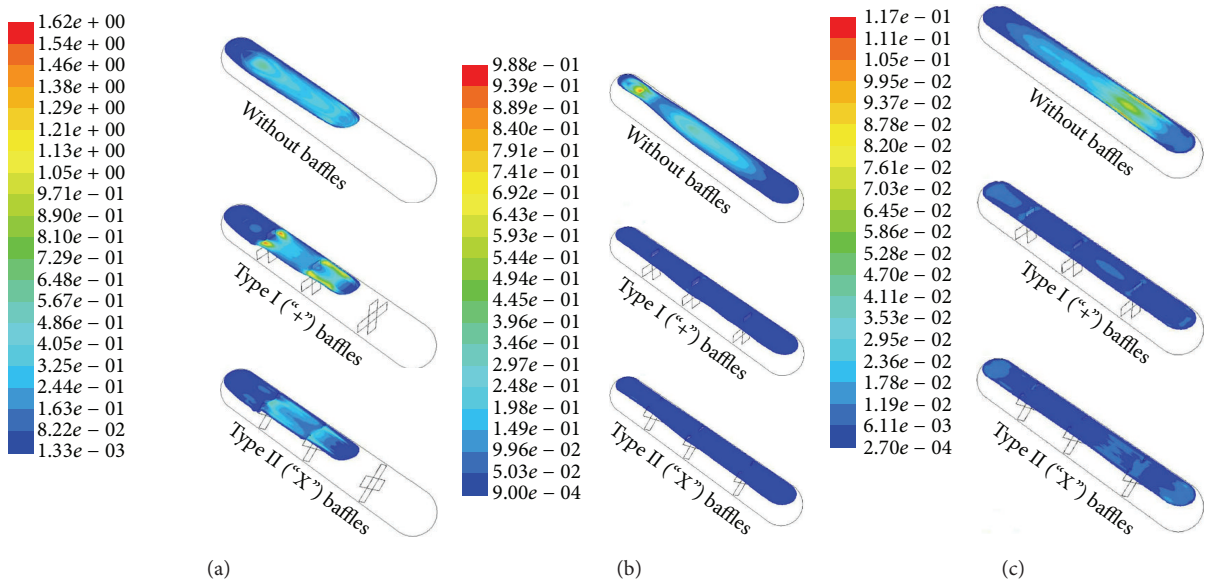

Figure 3: Contours of turbulent kinetic energy in the liquid-gas interface at (a) 1 s, (b) 10 s, and (c) 21 s after braking, for the three different configurations of road tanker.

2.4. Numerical Method. Finite volume numerical method (Finite Volume Method) used by Fluent software (ANSYS, Inc.) is used here to approximate the solution of partial differential equations that are used to represent the studied phenomenon.

Figure 2 shows the mesh on the system under study, which is hexahedral structured uniform in size and body-fitted with the geometry of the road tanker. To simulate the tanker without baffles 305,760 cells were used, and for simulations of tankers with baffles 293760 cells were used.

3. Results and Discussion

Figure 3 shows outlines of turbulent kinetic energy in the liquid-gas interface for the road tanker without baffles and for both configurations with baffles; the maximum and minimum values for (a) 1 s, (b) 10 s, and (c) 21 s after Stage I has been completed are shown.

Maximum values of turbulent kinetic energy as a function of time for the central longitudinal plane for Stage II are shown in Figure 4. It can be seen that the curve corresponding to the tanker without baffles is not the one with the highest turbulent kinetic energy at the beginning, however, after the initial moments of Stage II reach the highest value among the three configurations of road tankers studied, maintaining that characteristic and showing significant fluctuations, as time progresses until the fluid comes to rest. The curves

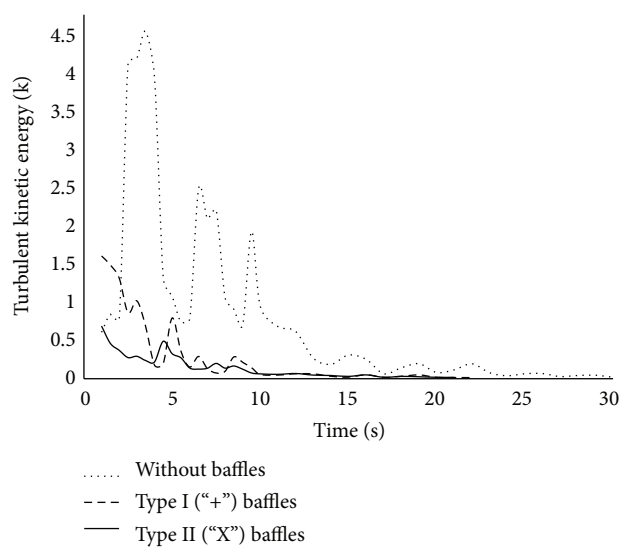

Figure 4: Maximum turbulent kinetic energy in the liquid-gas interface for the three road tanker configurations.

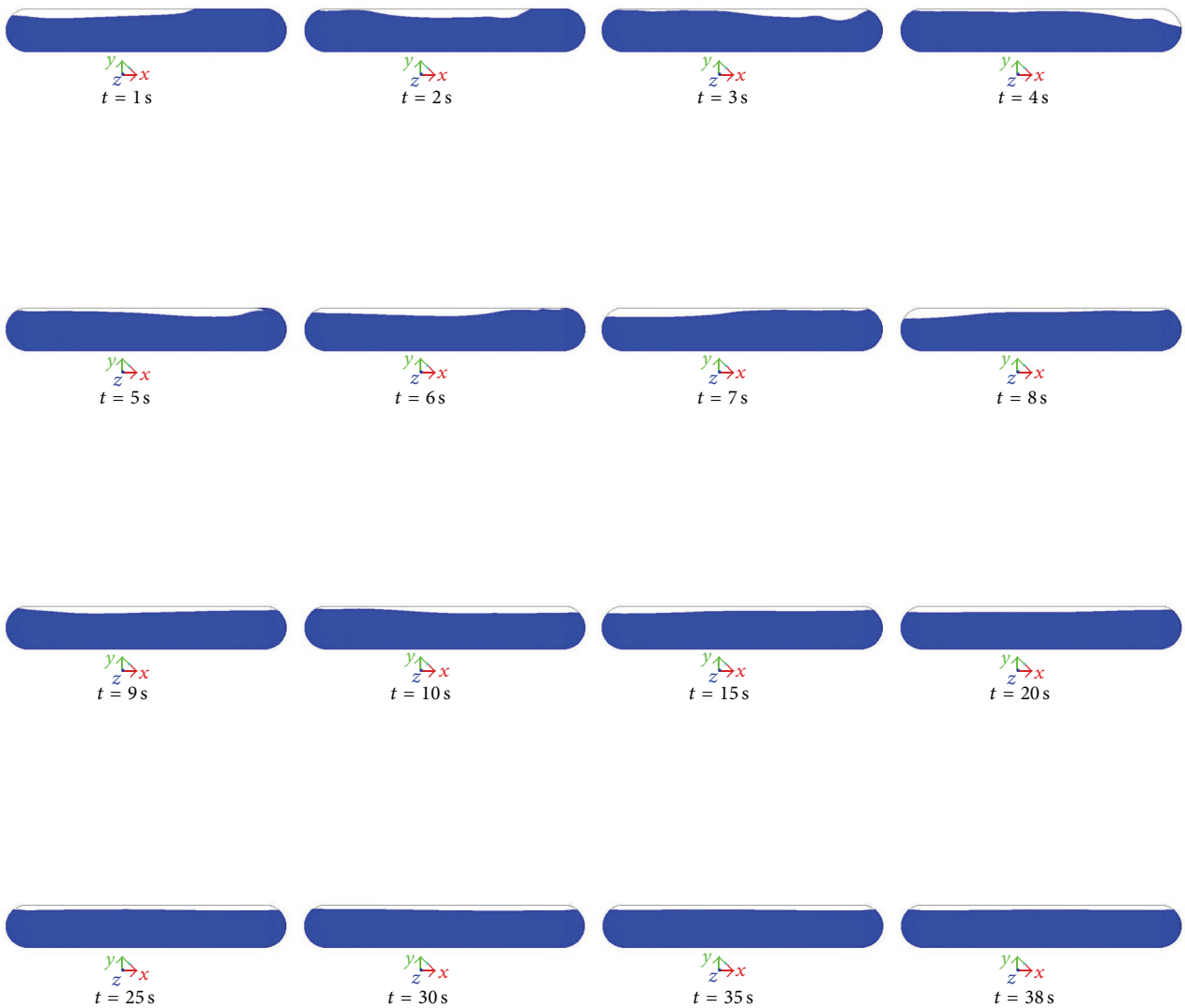

Figure 5: Behavior of the liquid during the sloshing evolution in the road tanker without baffles for Stage II.

corresponding to the tankers with baffles show a similar behavior as the tanker without baffles, but with less amplitude oscillations and reaching the rest of the fluid in less time.

From Figure 4 it also should be noted that (1) the road tanker with Type I baffles, during the first two seconds, starts with values of turbulent kinetic energy greater than those of the other two tankers, which can be due to the fact that when the liquid moves during that time it hits the vertical bars of the baffles, causing a sudden change of direction of the liquid, which does not occur in the other cases, because there is no surface with a similar location that could cause a phenomenon like this in them (Figure 3(a)) and (2) in the road tanker with Type II baffles the turbulent kinetic energy is generally lower than in the other configurations for the times considered. These behaviors can be corroborated in Figures 5, 6, and 7.

A criterion was established to determine the times required to reach the liquid resting in each one of the simulated tankers, based on the maximum turbulent kinetic energy values obtained for the liquid-gas interface. Thus, it was considered that when two time consecutive values of k showed an absolute difference equal to or less than

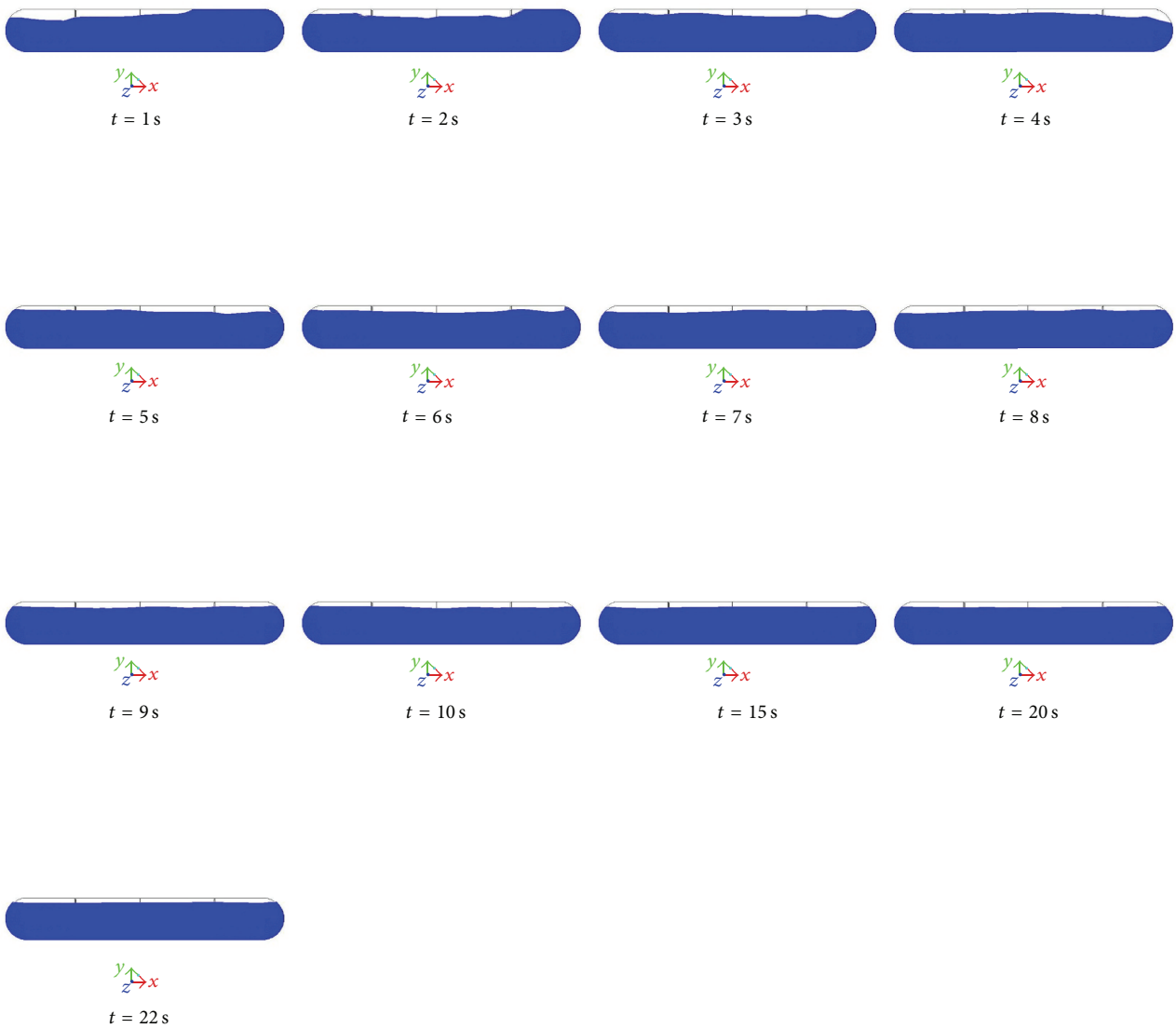

Figure 6: Behavior of the liquid during the sloshing evolution in the road tanker with Type I baffles for Stage II.

$0.001\,m^2/s^2$ the liquid had come to rest; stabilization times of the liquid are shown in Table 1. As expected, in the road tanker without baffles the liquid comes to rest in a longer time than in the tankers with baffles, which show very similar times to each other; the foregoing can be seen from schemes of liquid movement in the central longitudinal plane shown in Figures 5, 6, and 7.

The magnitude of the velocity vectors of the liquid during Stage II is also an important result of the study of the behavior of sloshing. Figure 8 shows the velocity vectors for the three configurations of road tankers for times of (a) 1 s, (b) 10 s, and (c) 21 s after starting Stage II. It can be seen that the road tanker without baffles has the highest values of velocity among the three configurations of tankers. Also, in the regions near the baffles zones of turbulence occurred.

Table 1: Stabilization times for the different configurations of road tankers.

Road tanker	Stabilization time (s)
Without baffles	38
Type I baffles	22
Type II baffles	21

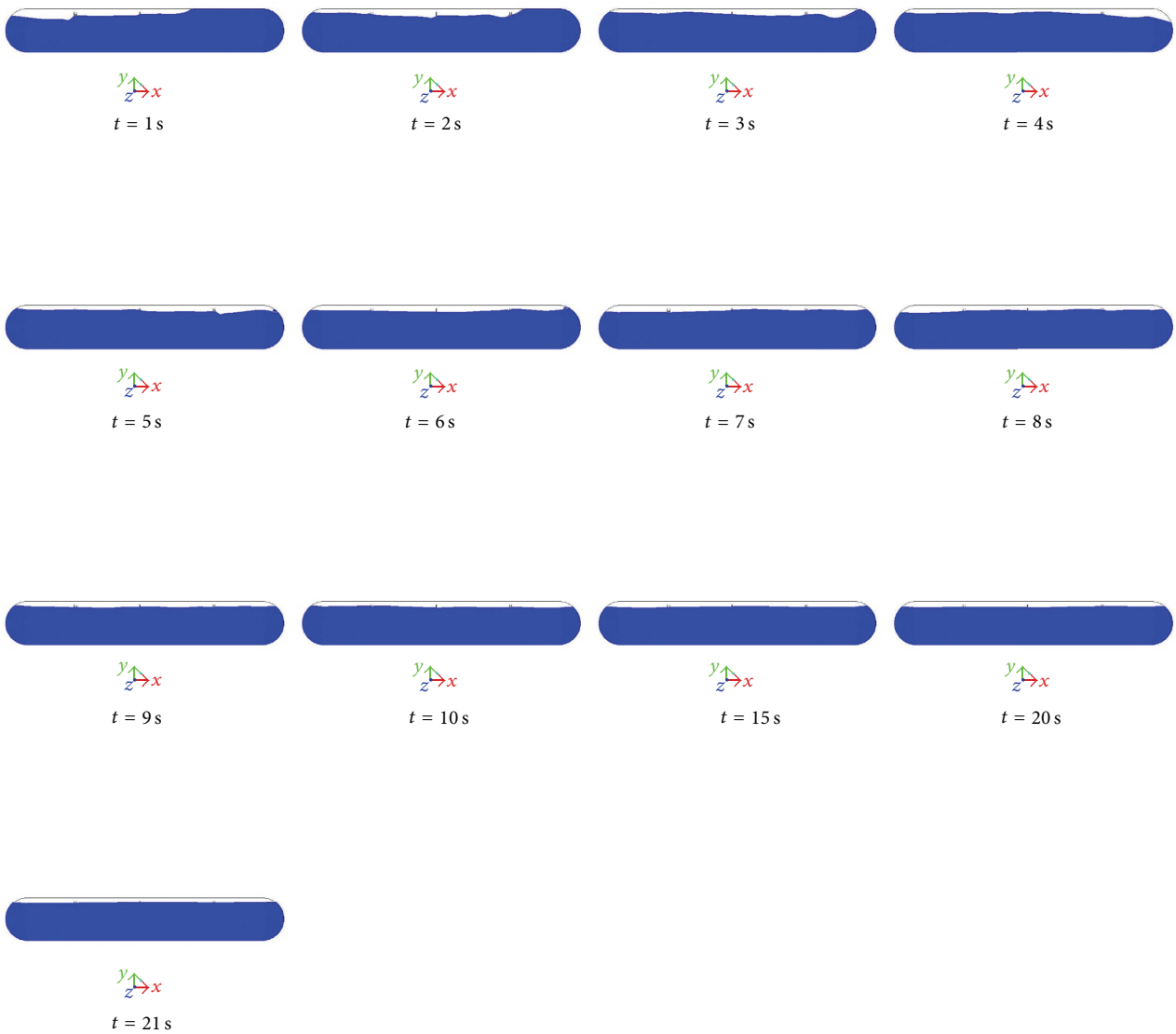

Figure 7: Behavior of the liquid during the sloshing evolution in the road tanker with Type II baffles for Stage II.

The magnitude of the maximum velocity for the central longitudinal plane with time for Stage II is shown in Figure 9. It can be seen that the curve corresponding to the road tanker without baffles shows great oscillation over time, until the liquid comes to rest. The curves for road tankers with Types I and II baffles show a similar behavior between them, with oscillations of smaller magnitude than in the tanker without baffles. However, among the three configurations of road tankers studied, the tanker with Type II baffles shows, in general, lower values of maximum velocity.

Results of simulations for the three different configurations of road tanker studied show that the use of baffles has a significant effect on the reduction of the liquid sloshing, reaching stabilization times 45% lesser for tankers with baffles (Type II) in comparison with the tanker without baffles. The opposition presented by the baffles locally diminishes the liquid motion, thereby reducing the overall energy of the liquid available to keep moving.

Although the results clearly show the advantages of the use of baffles, the fluid-dynamic behavior observed for these systems is not the same, although sloshing stabilization times are similar. The maximum turbulent kinetic energy values obtained (Figure 4) for the road tanker with Type I baffles

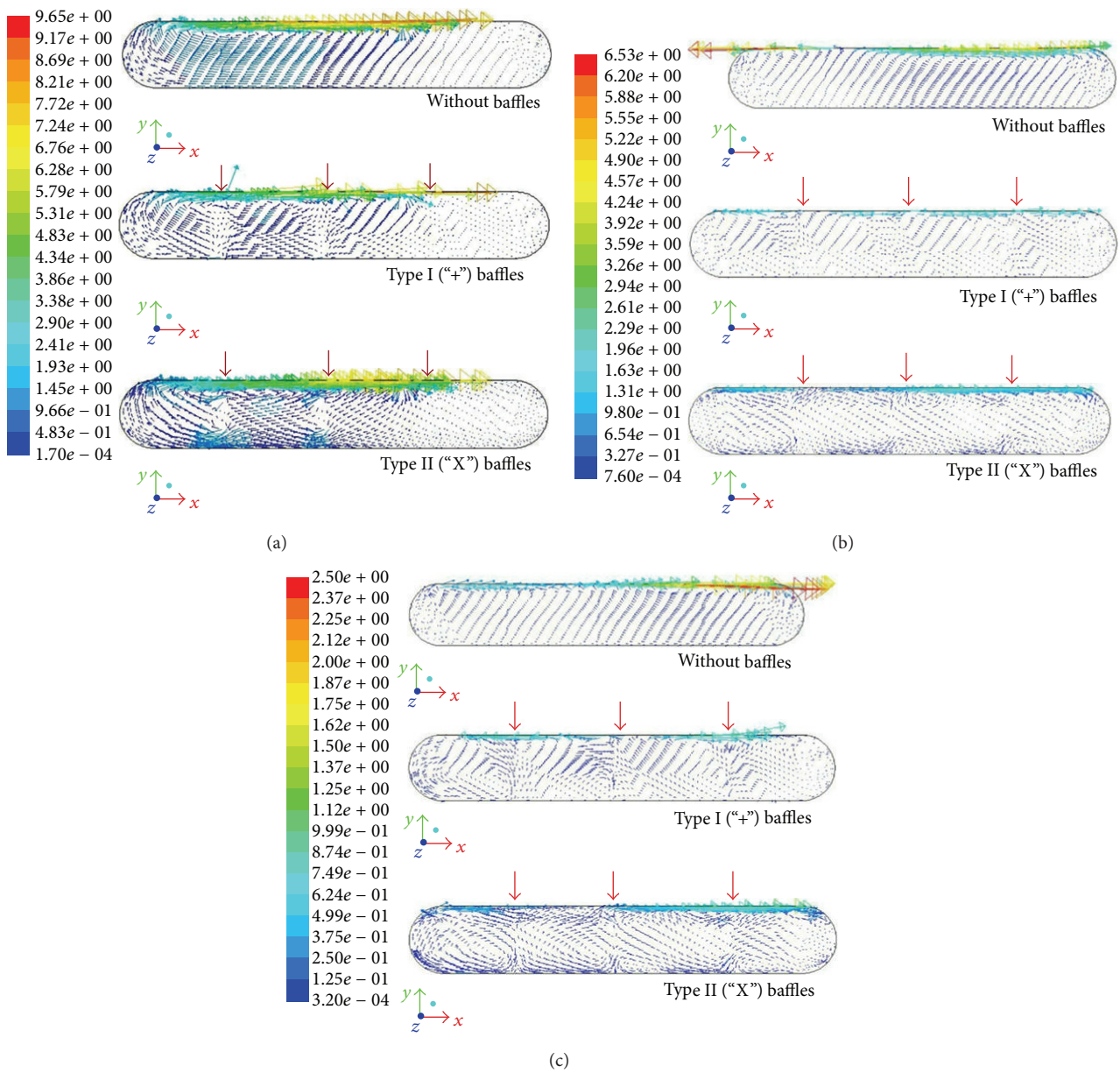

Figure 8: Magnitude of velocity vectors in the central longitudinal plane at (a) 1 s, (b) 10 s, and (c) 21 s after starting of Stage II for the three configurations of road tanker (red arrows indicate the position of the baffles).

are superior to those of the road tanker with Type II baffles; that is, in the first case, the liquid motion generates greater turbulence than in the latter, which eventually can lead to having a more violent sloshing, adversely affecting vehicle stability; this can be seen in the diagrams of Figure 8.

Additionally, maximum fluid velocities (Figure 9) for systems with either type of baffles show a similar behavior to that of the turbulent kinetic energy, with the highest values for Type I baffles, which means that the flow as a whole is more vigorous. Therefore, it can be considered that the use of Type II baffles has an advantage over Type I baffles, from the viewpoint of sloshing attenuation.

4. Conclusions

Times required in the road tankers with baffles for the liquid to come to rest were up to 45% lesser than the time required to reach the same state in the road tanker without baffles, which demonstrates the usefulness of this kind of structures.

Among the baffles configurations used nowadays in real road tankers (Types I and II), Type II looks like the best in terms of sloshing attenuation, given the comparatively low values of turbulent kinetic energy and fluid velocity.

It is considered that Type II baffles have the best characteristics in terms of vehicle control, due to a less vigorous sloshing that occurs when they are used.

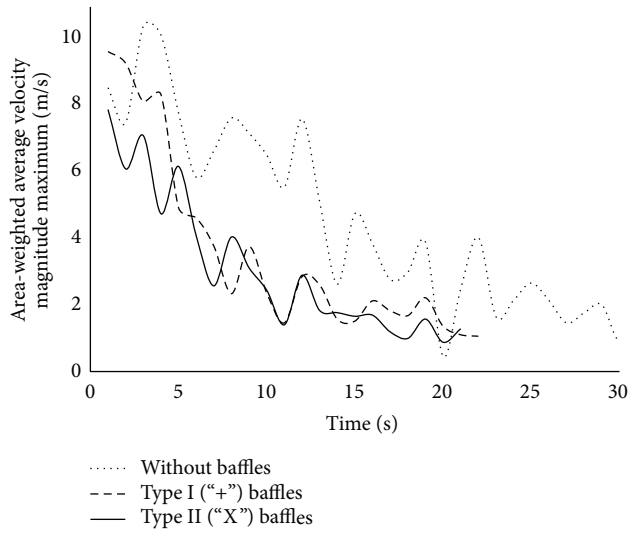

Figure 9: Maximum velocity in the central longitudinal plane for the three different configurations of road tanker.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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