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A Computational Investigation of the Effect of Geometric Parameters on the Discharge Rate of a Ship Opening

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Keywords: water discharge, numerical simulation, free surface, volume of fluid model

Abstract

The purpose of the research was to find a relationship between the geometric characteristics of an opening on deck and the water discharge rate. This study is aimed at the stability of open deck ferries and fishing vessels. The effective parameters on the discharge rate are the beam, depth of the water collected on the deck and the discharge gap height. In this study, CFD analyses for water discharge from a ship deck were conducted, and the commercial code FLUENT was used to conduct the simulations. A two dimensional unsteady 2nd order solver in time and space was used for the simulation. The two-phase free surface model was simulated by the Volume of Fluid (VOF) model.

Using the water discharge, the instantaneous depth Froude number was calculated as a part of the non-

dimensional simulation. The effect of geometric parameters on the water discharge rate was investigated by keeping two parameters fixed while changing the third parameter. For each parameter, three different values were evaluated and the comparisons of all the twenty seven possible combinations of the effective parameters were presented. Results were compared with the experimental results obtained earlier at UBC.

Introduction

Water collection due to the interaction of vessels motion and ocean waves usually causes significant problems for ferries and fishing vessels. These problems can be in the forms of damage to people on deck, ship facilities, and loss of stability. In order to avoid water collection on the deck, several experiments were conducted and a minimum freeboard requirement was suggested [2-4]. There were also numerical simulations conducted to investigate the effect of the water collection on deck during roll motion of a ship [5] and to predict the green water and wave loading [6]. Experimental research at the University of British Columbia showed that the

discharge rate from an opening of a ship is dependent on certain geometric parameters of the opening as well as collected water on deck [1]. These parameters, as shown in Figure 1 are: the length of the tank (presenting half beam of the vessel), the opening height (gap height) and the height of the water collected initially.

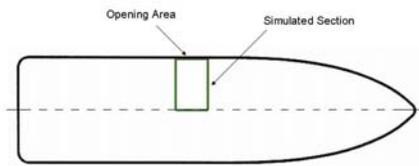


Figure 1.a Schematic of the simulated area

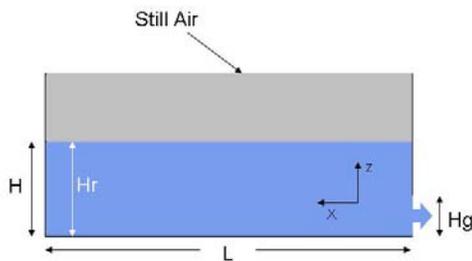


Figure 1.b Model for water discharge

The purpose of the current research was to computationally investigate the effects of the above mentioned parameters on the discharge rate from a ship opening. This research also shows that a great deal of reduction in cost and time spent on experimental modeling can be achieved by conducting computational simulation. By choosing three different tank lengths, three collected water heights and three opening heights,

twenty seven combination models were built and the discharge rate was computed as a function of time. The results were then non-dimensionalised. Although the open channel flow theories state that in a steady-state open channel flow over a weir the Froude number is at most unity, numerical results show that the Froude number will exceed unity in unsteady conditions. This may be attributed to the generation of waves inside the tank created by the discharging water. These waves propagate back and forth in the tank and cause the Froude number at the outlet to exceed unity. The fact that the Froude number exceeds unity in unsteady condition has been shown previously in the experiments conducted at the University of British Columbia [1].

CFD Model

The commercial code, FLUENT, was used as the solver while GAMBIT was used as the modeling and meshing software. Twenty seven two-dimensional models were created to investigate the effect of three important parameters affecting the discharge rate from a tank. These changing parameters and their values are displayed in table 1.

Table 1

Parameter	Values
Tank Length (L) [ft]	2,4, and 6
Water Height (H) [in]	6,10, and 14
Discharge Gap Height (Hg) [in]	2,4, and 6

A quadrilateral structured grid with appropriate aspect ratio was used to mesh the domain (figures 2.a and 2.b). A grid refinement study was conducted to

ensure that the grid is sufficiently fine for the required accuracy (figures 3.a and 3.b). The final mesh includes 28800 to 115200 quadrilateral structured cells depending on geometry. An unsteady, two-dimensional, segregated, 2nd order in time and space solver was used for the simulation. Air and fresh water were used as the working fluids. In addition, a Volume Of Fluid (VOF) method was used to simulate the two-phase flow and the free surface. The free surface was defined as the region where the volume fraction of water is 0.5. To record the value of the instantaneous water level 100 nodes were defined at the rear part of the tank. The volume fraction of water at each node was recorded every 0.2 seconds and written to a file. The water level was determined by identifying the point at which the volume fraction of water was 0.5. The instantaneous water discharge rate was also recorded at each time step (0.001 seconds). The results were subsequently non-dimensionalised to obtain dimensionless time and Froude number at the outlet.

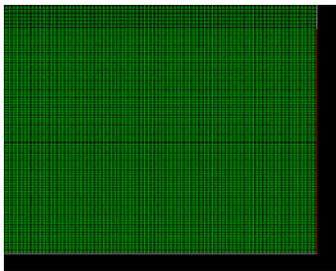


Figure 2.a Grid at the outlet

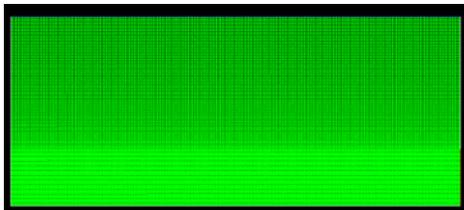


Figure 2.b Grid of the domain

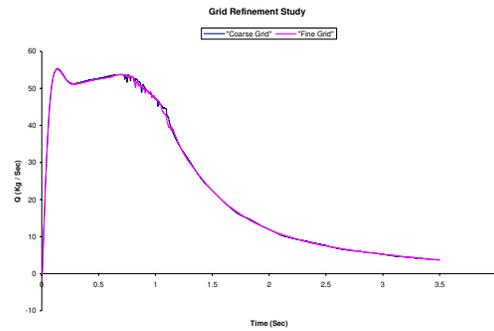


Figure 3.a Grid refinement study for a coarse (28800 cells) and fine (115200 cells)

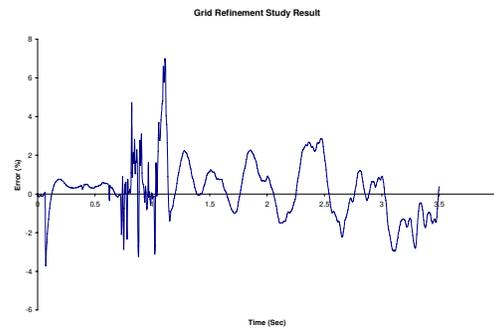


Figure 3.b Difference between the coarse grid results and fine grid results in percent

Results and Discussion

After obtaining the mass flow rate at the outlet, the instantaneous water height at the rear of the tank and given the outlet area and real time of the simulation, the depth Froude number and time were calculated using Equation 1 and Equation 2.

$$Fn = \frac{(Q/A)}{\sqrt{g * Hr}} \quad (1)$$

$$t_n = t \sqrt{\frac{g}{H_r}} \quad (2)$$

The non-dimensionalised results for all twenty seven combinations are presented in figures 4 to 30. Figures 4 to 12 show the effect of the tank length on the discharge rate from the opening. Figures 13 to 21 show the effect of the initial water height. Figures 22 to 30 show the effect of the gap height on the discharge rate. As an extension to the current research a much larger tank measuring twenty feet in length was examined with the initial water level set at 14 inches and the gap height set at 4 inches. Figures 31.a through 31.d show the contours of the volume fraction of water for this problem.

Tank Length Effect

Figures 4 through 12 reveal that in all cases Froude number starts from zero and reaches a maximum value (the first sharp peak point). This maximum value is almost the same for all the cases with the same initial water level and gap height. In other words, the value of the first maximum point is not highly dependent on the tank length. After the first maximum point, the tank length effect becomes more noticeable and different tank lengths generate different curves, each of which reach a specific second maximum point. The magnitude of these secondary peaks generally increases with an increase in tank length. In addition, it takes longer time for the longer tank to reach the second peak point. Thus, the longer the tank is, the longer it takes to reach the second peak, and the greater the second peak is. Another important fact that can be observed in these figures is that in some cases there is only two extremums while in others there are multiple extremums. The physical interpretation of this phenomenon can be explained by

observing an animation of the simulations results. The animation reveals that when the tank length or initial water height are large or when the gap height is small (which can result in slower water discharge) an extra pressure force is exerted at the outgoing flow and causes the Froude number exceed one (which is predicted for a steady state flow). If the discharge takes longer, waves start to slosh back and forth in the tank (see figures 31.a through 31.d). It can be seen from the animations that the number of times that these waves go back and forth is equal to the number of peak point of on the Froude number vs. non-dimensional time curve. The amplitude of the waves determines how sharp the curves are at the extremums.

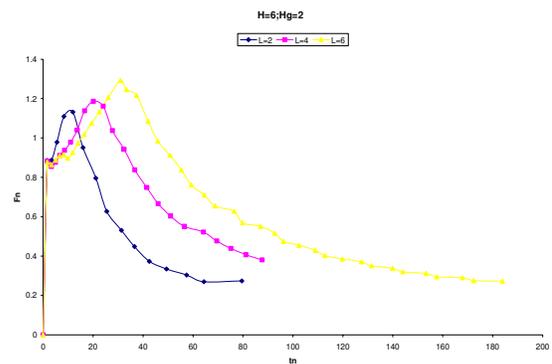


Figure 4 H=6 in ; Hg=2 in

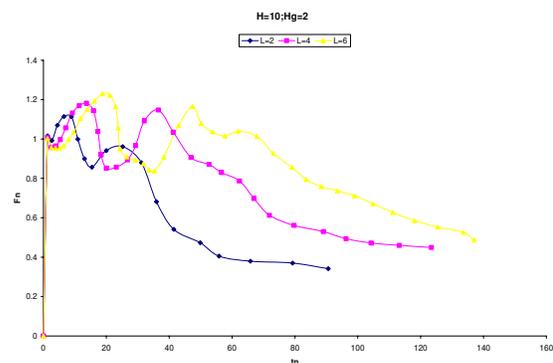


Figure 5 H=10 in ; Hg=2 in

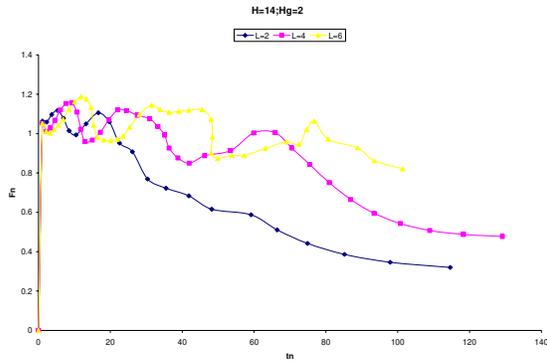


Figure 6 H=14 in ; Hg=2 in

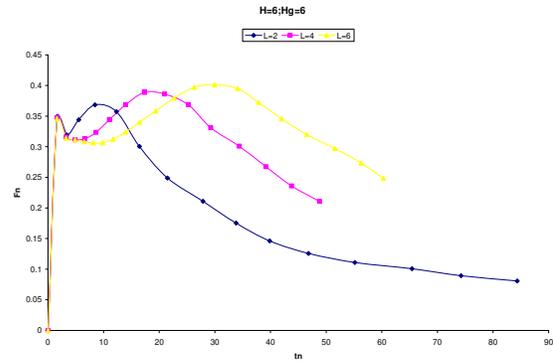


Figure 10 H=6 in ; Hg=6 in

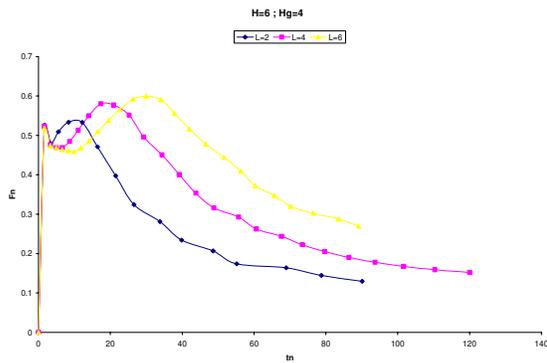


Figure 7 H=6 in ; Hg=4 in

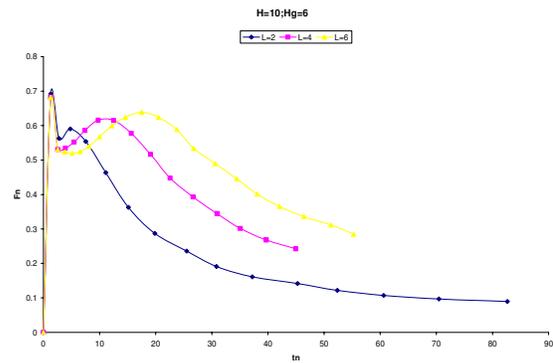


Figure 11 H=10 in ; Hg=6 in

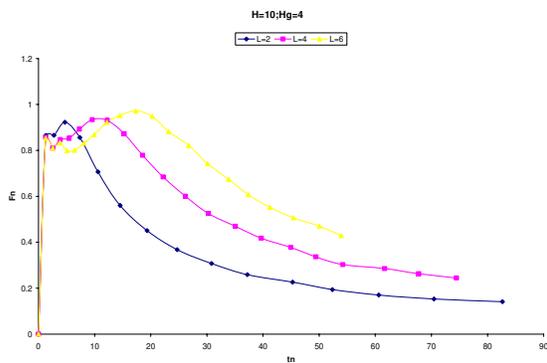


Figure 8 H=10 in ; Hg=4 in

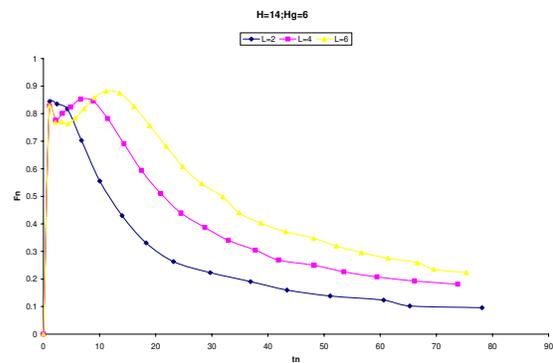


Figure 12 H=14 in ; Hg=6 in

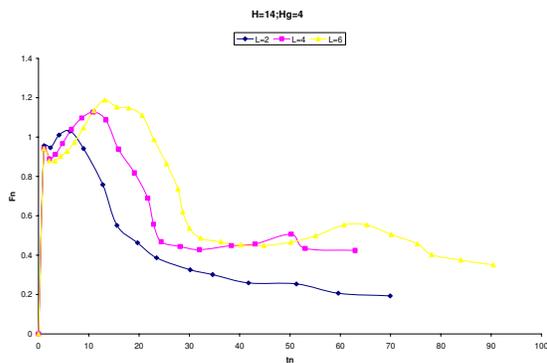


Figure 9 H=14 in ; Hg=4 in

Initial Water Height Effect

Figures 13 through 21 show that the increase in water height causes the value of the first peak point to increase. Moreover, the increase in the water height causes the second peak to occur earlier in all cases. In some cases, however, the maximum value of the second peak increases with the increase in water height (figures 16 to 21) while in other cases it decrease with the

increase in water height (figures 13 to 15). This behavior occurs as a result of a blockage of water discharge (chocking of the outlet) due to the small outlet gap height and causes a pressure pulse propagating back into the tank. On the other hand, when the gap height is large enough (figures 16 to 21) the discharge rate (Froude number) increases when the volume of water to be discharged increases.

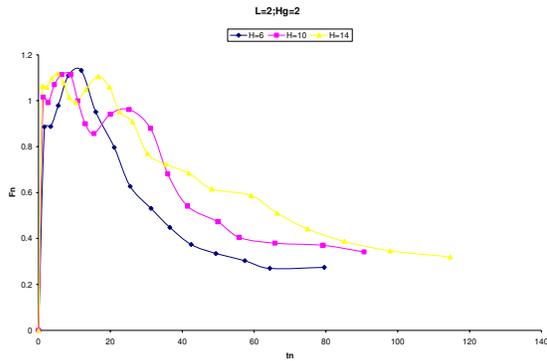


Figure 13 L=2 ft ; Hg=2 in

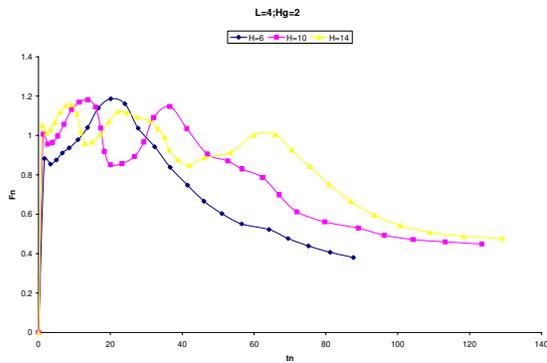


Figure 14 L=4 ft ; Hg=2 in

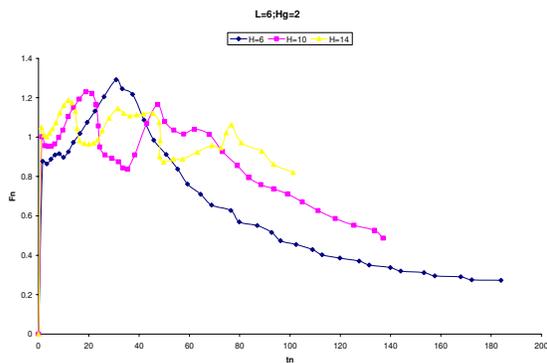


Figure 15 L=6 ft Hg=2 in

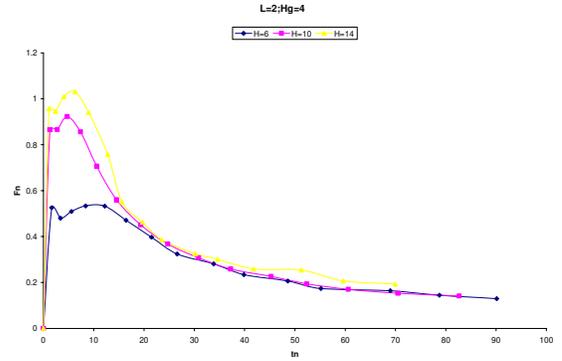


Figure 16 L=2 ft ; Hg=4 in

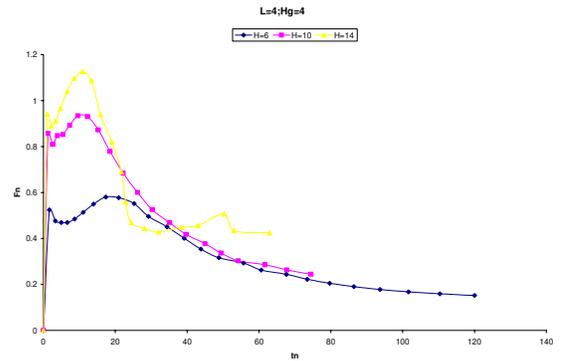


Figure 17 L=4 ft ; Hg=4 in

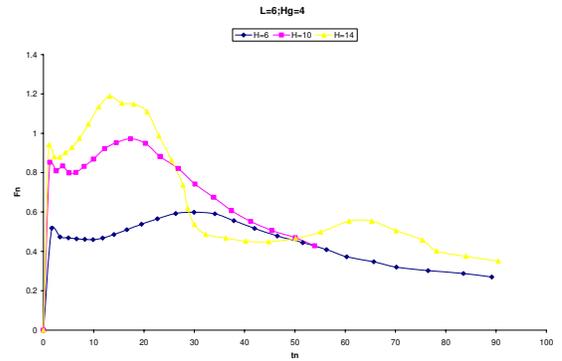


Figure 18 L=6 ft ; Hg=4 in

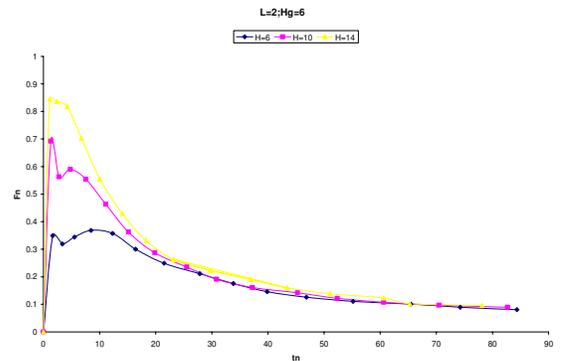


Figure 19 L=2 ft ; Hg=6 in

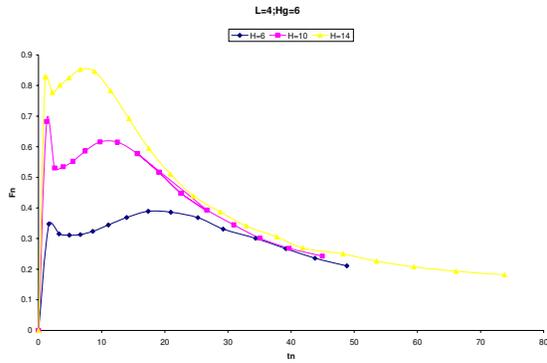


Figure 20 L=4 ft ; Hg=6 in

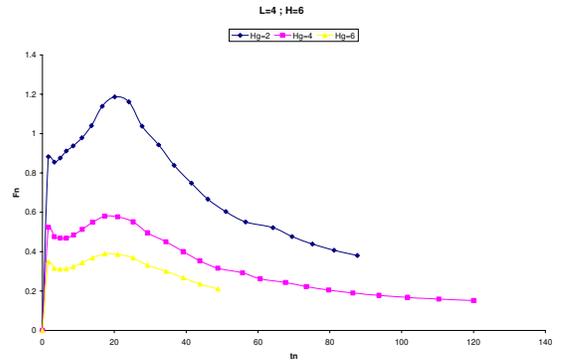


Figure 23 L=4 ft ; H=6 in

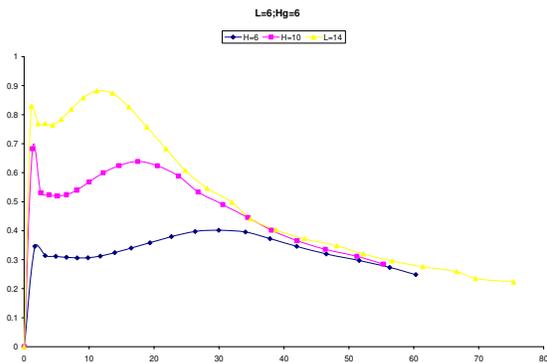


Figure 21 L=6 ft ; Hg=6 in

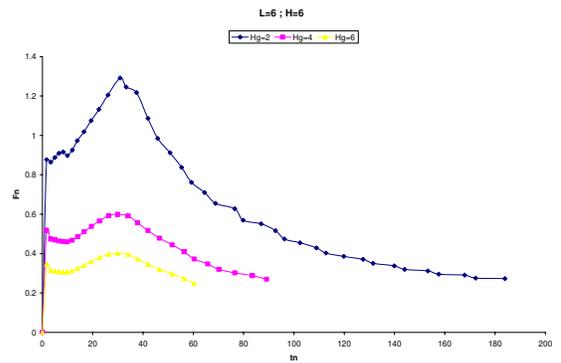


Figure 24 L=6 ft ; H=6 in

Gap Height Effect

As it can be seen in figures 22 through 30 the smaller the gap height the larger the maximum Froude number. Also, when the initial water height increases, the effect of the gap height is minimized and the difference between the maximum Froude numbers becomes smaller.

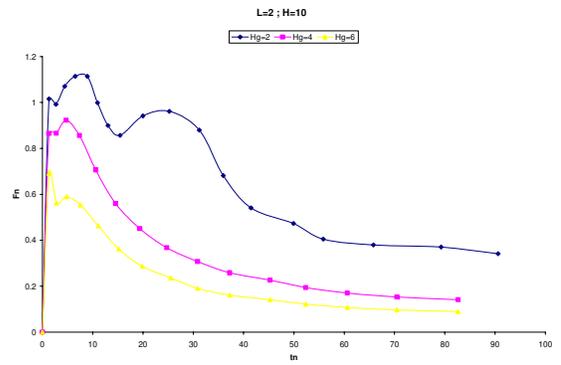


Figure 25 L=2 ft ; H=10 in

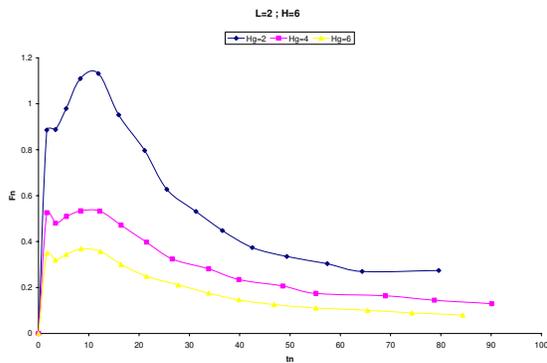


Figure 22 L=2 ft ; H=6 in

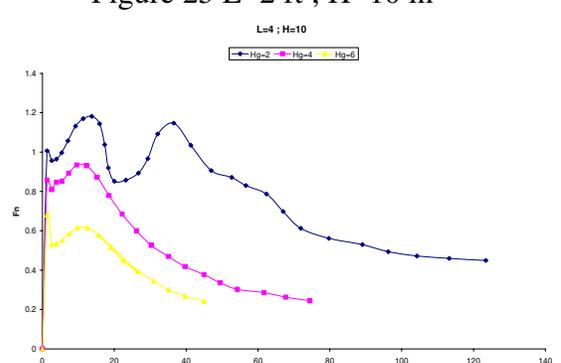


Figure 26 L=4 ft ; H=10 in

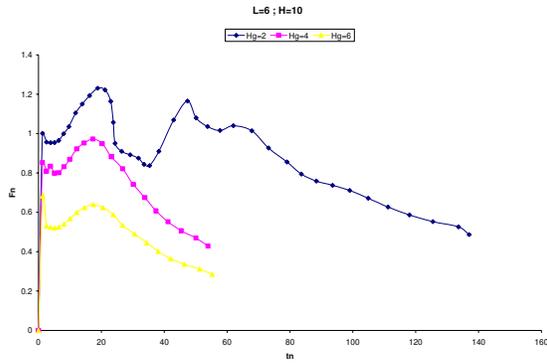


Figure 27 L=6 ft ; H=10 in

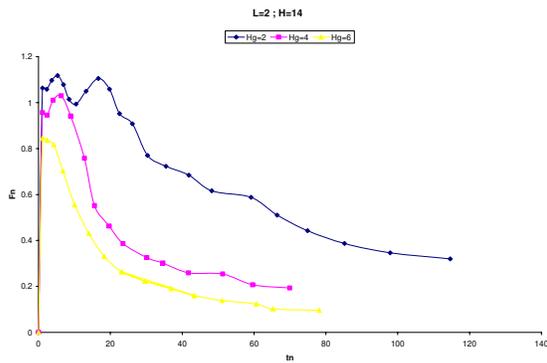


Figure 28 L=2 ft ; H=14 in

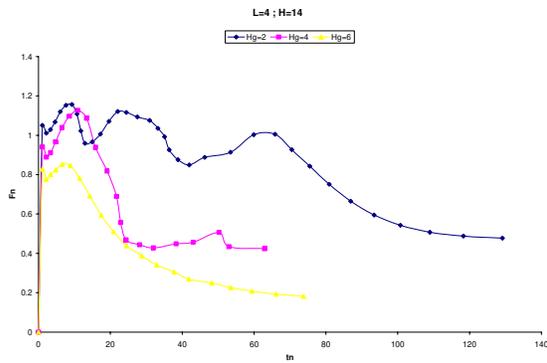


Figure 29 L=4 ft ; H=14 in

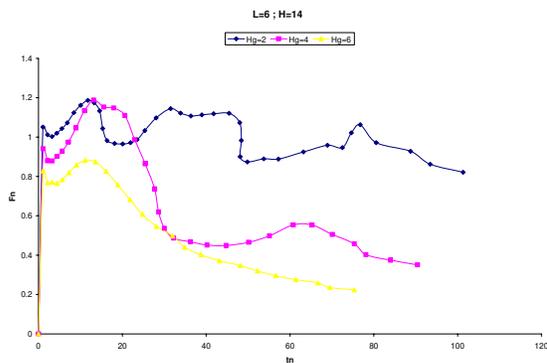


Figure 30 L=6 ft ; H=14 in

A comparison of the computational results to previous experimental results obtained at the University of British Columbia [1], shows that in some cases there is a relatively significant difference between the experimental results and computational solutions. This difference can be due to the errors in measurement of the instantaneous water level at the rear part of the tank. The source of this error was the low resolution of the images which had been taken during the experiments. The noise of weight sensors was another source of error in the experiments. Another reason for the discrepancy found between numerical and experimental results may be due to the fact that the numerical simulations ignore 3D effects.

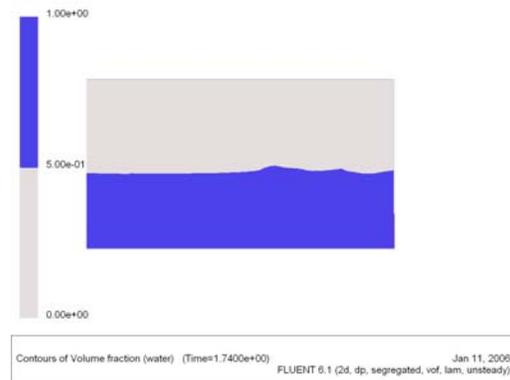


Figure 31.a Contours of Volume Fraction of Water (t=1.7400 sec)

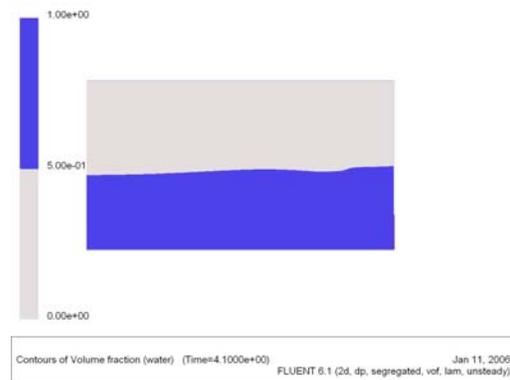


Figure 31.b Contours of Volume Fraction of Water (t=4.100 sec)

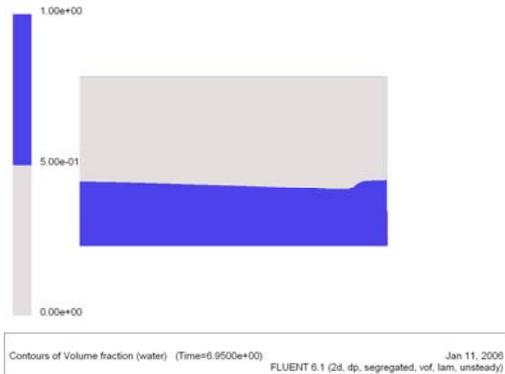


Figure 31.c Contours of Volume Fraction of Water (t=6.9500 sec)

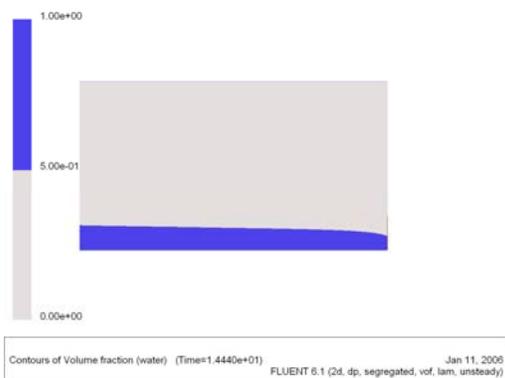


Figure 31.d Contours of Volume Fraction of Water (t=14.4400 sec)

Conclusion

This paper focused on numerically predicting the influence tank length, water height and opening size has on the discharge rate of water from a ship opening.. Twenty seven numerical models were created to study the relationship between the parameters. The results showed that depth Froude number exceeds unity in unsteady conditions. Furthermore, in certain cases, especially when the gap height is small, waves begin to propagate in the tank. These waves affect the discharge rate significantly. On the other hand, in most cases which included none or minimal wave propagation, the discharge rate increased when the tank length and water height increased or when the gap height decreased. CFD

simulations proved to be a very useful tool for this study and are warranted for use in further studies on this topic, especially for cases involving large tank sizes not feasible for studying experimentally.

Nomenclature

A	Cross sectional area of the opening
L	Flooded length of the tank
H	Initial water height inside the tank
Hg	Height of the opening
Hr	Instantaneous water height at the rear end of the tank
Fn	Depth Froude Number
tn	Non-dimensional time
Q	Volume flow rate
t	Real time of simulation
G	Gravitational acceleration

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