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Assessment of Peak Upsurge Height Adopting Simulation Analysis

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Abstract: Surge tanks are water storage devices provided on the upstream of a pump house. The main purpose of a surge chamber is to protect the pipe line from excessive surge pressures. During the power failure or sudden shut down of pump(s), the flow in the pipe line is diverted into the surge tank. The present study was carried out for Kalwakurthy Lift Irrigation Scheme (stage-III) to predict the peak upsurge height in the surge chamber. The pressure oscillations in the surge tank for different unsteady flow situations with various pump operating conditionswas analyzed in ANSYS – Fluent software. A user-defined function, by means of macro generated based on the VOF - multiphase analysis was adopted. The peak upsurge height was evaluated analytically for one, two and three-pump shutdown conditions. Further, the study was extended to estimate the peak upsurge height by means of two different widely adopted turbulence models viz., k-Epsilon and k-Omega. The results obtained from the simulation analysis were found to be in good consonance with the analytical results for all the three unsteady flow conditions.
Keywords: Pump Shutdown, Time Period, Pressure Oscillations, Peak Upsurge Height, K-ε, K-Ω

I. INTRODUCTION

A surge tank is defined as a storage reservoir at the downstream end of a long low-pressure tunnel having a mild gradient. The purpose of surge tank is to safe guard the pipe section from excessive surge pressures. The high surge pressures could cause damage or even cause collapse of the pipe line/tunnel that would be very expensive to repair. Hence, the important aspects in the design of surge tank are the evaluation of periodic time (T_P) and pressure oscillations. When the valve is closed, the flow in the pipe line is diverted into the surge tank. The difference of flow between the pipe line and that entered after the valve closure, causes a rise of water level in the surge tank. The water level in the surge tank accelerates upwards, rises above the liquid level in the reservoir and comes to rest. An energy imbalance is created as water rises above the level of the reservoir. Hence, the surge tank level begins to fall and water flows back into the pipe line. The cycle is repeated with mass oscillations of water in the pipe line and the surge tank until it is gradually damped out by friction [1].

The present study was focused to predict the condition of unsteady flow that is associated with an emergency viz., power failure, breakdown in pumps, emergency shutdown of pumps, etc. The peak upsurge height in the surge chamber obtained from the analytical calculations was compared with ANSYS – Fluent software results.

The physical modeling studies were carried out by Chandramohan et al (2007) to evaluate the peak upsurge and down surge heights for 1:30 scale model of Rajiv (Bheema) Lift Irrigation Scheme. The analysis was carried out at Hydraulic Engineering Laboratory of IIT-Bombay. The studies were taken for three varying sizes of surge pool viz., 7.0 m, 20.0 m and 25.0 m. The experiments were based on one pump starting and shut down, third pump starting while the first and second were in running condition and three pumps shut down. The authors concluded that, with the increase in the width of the surge pool the amplitude of the surge oscillations was observed to decrease [2].

Shaligram (2011) carried out hybrid mathematical modeling studies based on FEM for the same case study of Chandramohan et al. The author evaluated the peak upsurge and down surge heights for 7.0 m, 20.0 m and 25.0 m. width of surge pools emphasizing on the size of the pool. The study concluded that, 20m width surge tank showed satisfactory results when compared with analytical results [3].

II. CASE STUDY

Agriculture is the world's largest industry and its demand is rapidly increasing with the growth in the world's population. Therefore, in order to meet the demand, the available water supplies play a major role. Based on the geological and topographical condition of the place, it becomes essential to lift the water wherever necessary. Many lift irrigation schemes are being planned to draw maximum water and thereby increase the command area. One among such major lift irrigation projects is Kalwakurthy Lift Irrigation Schemes. The hydraulic particulars of the present case study (stage-III) are presented in Table 1[4].

Table 1
Hydraulic Particulars of Study Area

Description of Components	Dimensions
Maximum Design Discharge in the tunnel	92.05 cumec
Discharge Capacity of the pump	18.41 cumec
Number of pumps	05
Length of the tunnel	6156.0 m
Length of the surge tank	40.0 m
Width and Height of the surge tank	94.0 m and 97.0 m
Length of the delivery main	55.0 m
Velocity in the tunnel	2.392 m/s
Velocity in the delivery main	0.936 m/s
A Butterfly valve was provided on the downstream side of the turbine pump to avoid the failure of the pipe line under adverse conditions.	

III. METHODOLOGY

The present investigation was carried out by means of analytical calculations and simulations using Fluent software using k-Epsilon and k-Omega turbulence models.

A. Analytical Calculations

The analytical computations were performed based on the momentum and continuity equations as given in the following eq. (1) and eq. (2). The definition sketch highlights all the terminology as detailed in Fig. 1 [1].

$$\frac{dQ_t}{dt} = \frac{gA_t}{L}(-Z_{st} - cQ_t|Q_t|) \qquad (1)$$

$$\frac{dz}{dt} = \frac{1}{A_{st}}(Q_t - Q_{dm}) \qquad (2)$$

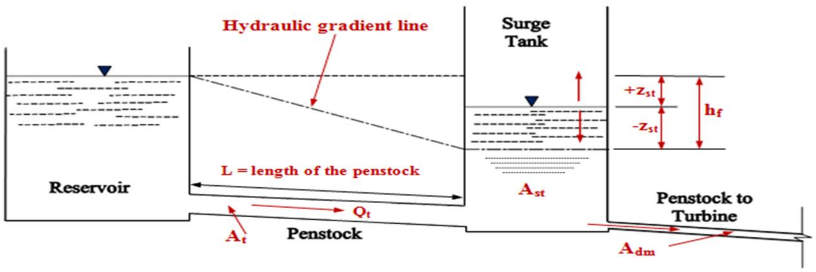

Fig. 1 Definition Sketch of Surge Tank

The friction factor (f) for the tunnel and the pipe on the d/s of the surge tank were estimated using the following eq. (3). The periodic oscillations (T_p) along with the surge oscillations (Z_{st}) were computed using eq. (4) and eq. (5) as stated below [5].

$$\frac{1}{\sqrt{f}} = \left\{2 * \left(\log\left[\mathrm{Re}\sqrt{f}\right]\right) - 0.8\right\} \quad \text{…………….. (3)}$$

$$T_P = 2\pi\left(\frac{L}{g}.\frac{A_{st}}{A_{dm}}\right)^{0.5} \quad \text{…………. (4)}$$

$$Z_{st} = V_t.\frac{A_{dm}}{A_{st}}.dt \quad \text{…………….. (5)}$$

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Volume 10 Issue II Feb 2022- Available at www.ijraset.com

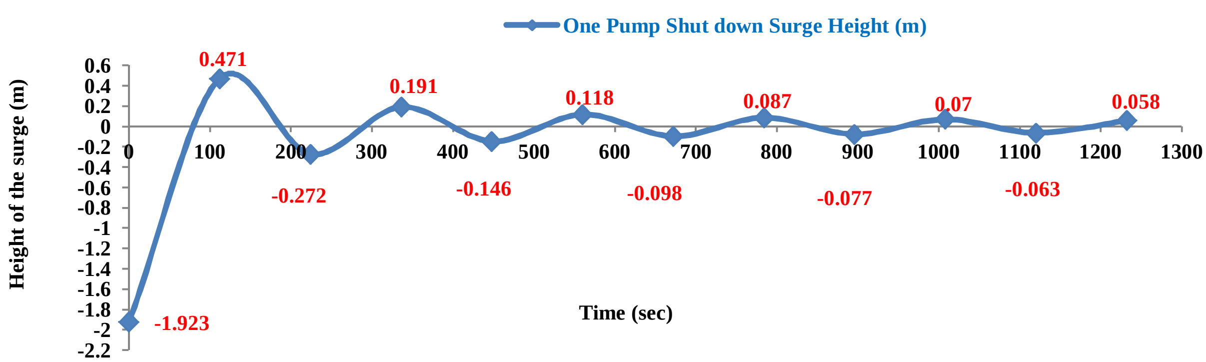
The pressure oscillations created due to power failure should damp down with time. This is possible when the area of the surge tank is according to the eq. (6) [6].

$$\left.\begin{aligned} A_{st} &\geq A_{st(Thoma)} \\ A_{st(Thoma)} &= \frac{A_t L_t V_t^2}{2gh_f\left(H_g - h_f\right)} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ (6)$$

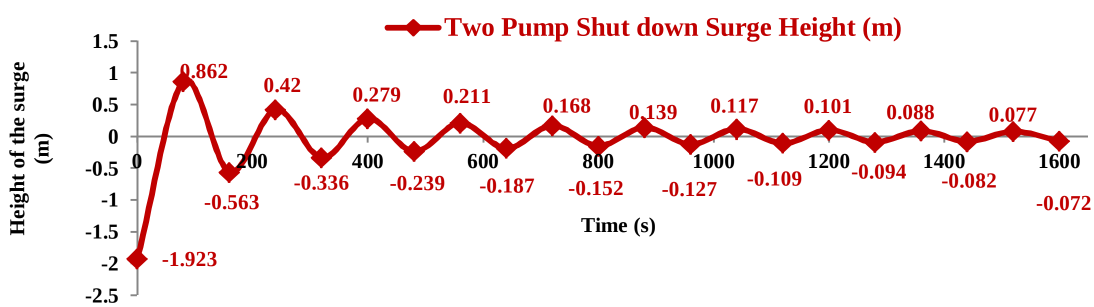
$$F.S = \frac{A_{st}}{A_{st(Thoma)}} \quad \ldots\ldots\ldots\ldots\ldots\ (7)$$

where,
Re = Reynolds number of flow in the tunnel and delivery main
L_{dp} = Length of the delivery main, m
f = Friction factor of the pipe material
A_{dm} = Area of the delivery main pipe, m^2
V = Velocity in the delivery main, m/s.
dt = Time interval, s
H_g = Difference between reservoir level and bottom of surge tank
A_t = Area of the tunnel, m
L_t = Length of the tunnel, m
V_t^2 = Flow velocity in the tunnel, m/s
A_{st} = Area of the surge tank, m^2
h_f = head loss due to friction, m
F. S = Factor of safety of plan area of the surge tank

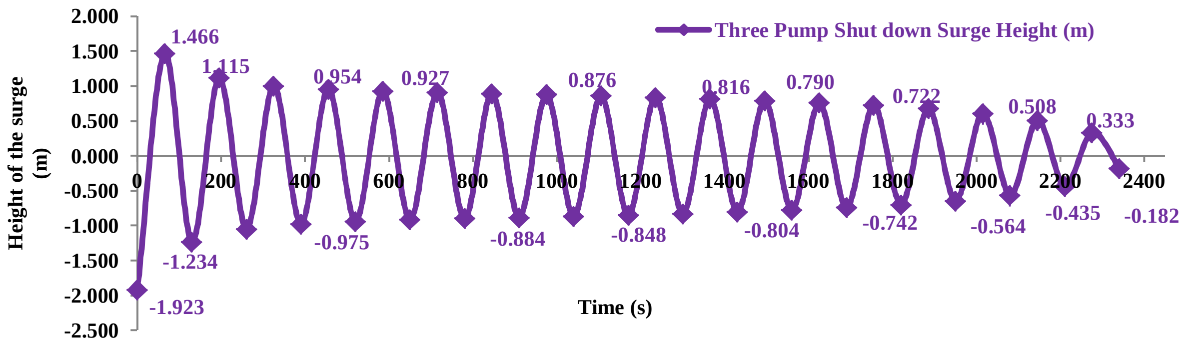
The analytical calculations were carried out and the result of one, two and three pump shutdown situations are detailed in Fig. 2 (a) to (c).



(a) One Pump Shutdown



(b) Two-Pump Shutdown



(c) Three Pumps Shutdown

Fig. 2 Surge Oscillations and Height

The study was further extended to optimize the size of the existing surge tank due to the fact that, the peak upsurge height for three pumps shutdown condition was observed to be 1.493 m only. Hence, an attempt was made to reduce the volume of the surge tank to the extent possible. However, the difference in elevation between tunnel invert and ground level (GL) will always remains the same. Therefore, the depth of the surge tank cannot be modified as the water needs to be drawn by means of gravity. Hence, only the plan area of the tank can be adjusted. The width of the tank to the extent possible was reduced, keeping in view of space requirements for accommodating the pumps. However, the plan area of the surge tank cannot be decreased beyond the value obtained from eq. (6), i.e., 1705 sq.m. Hence, the analytical calculations were performed for three pumps shutdown condition, having a plan area of 2200 sq.m. The initial liquid level in the surge tank was at an elevation of 392.104 m. The Minimum Draw Down Level (MDDL) to be maintained in the surge tank is 389.653 m. Therefore, the difference in the above two levels work out to be 2.351 m. From the calculations detailed in Fig. 3, for optimized size of the surge tank, the downsurge height (2.413 m) beyond 750 s was observed to drop below the MDDL. Hence, the factor of safety was evaluated from eq. (7) for the existing tank. It was found that, the plan area provided for the surge tank was reasonable.

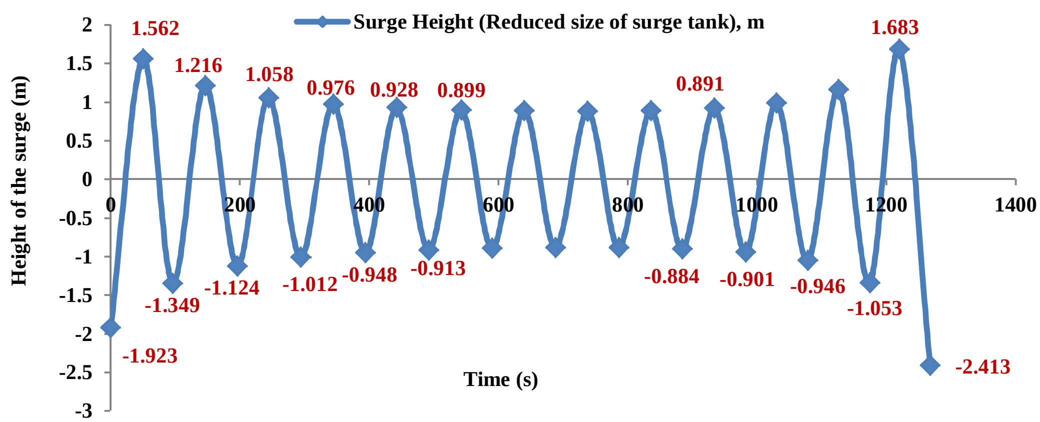


Fig. 3 Surge Oscillations for Three Pump Shutdown (For Reduced Size of the Tank)

B. Numerical Simulations

The commercially available ANSYS – CFD (Fluent) was adopted to for solving Reynolds Averaged Navier Stokes (RANS) equations using Finite Volume approach. This software was implemented to evaluate the peak surge height for different unsteady flow situations with various pump operating conditions. The process was carried out in three stages viz., 3D geometry creation as shown in Fig. 4 and mesh generation containing 3,52,162 nodes and 3,08,709 elements as detailed in Fig. 5. The model was distorted in length wise in order to accommodate the full tunnel length of 6156 m with the scale ratio of 1:20. The other dimensions of the surge tank with respect to width and height were taken same as in the prototype. The extraction of results was based on the volume fraction values. The water level in the surge tank was initialized at a 21.0 m above the tank bottom of the surge tank as shown in Fig. 6.

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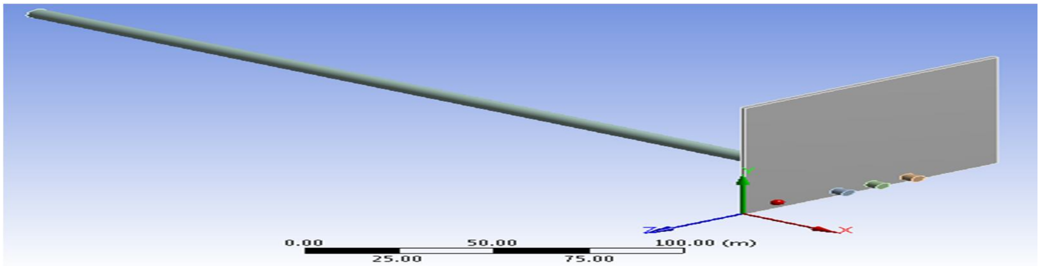

Fig. 4 Geometry of Surge Tank

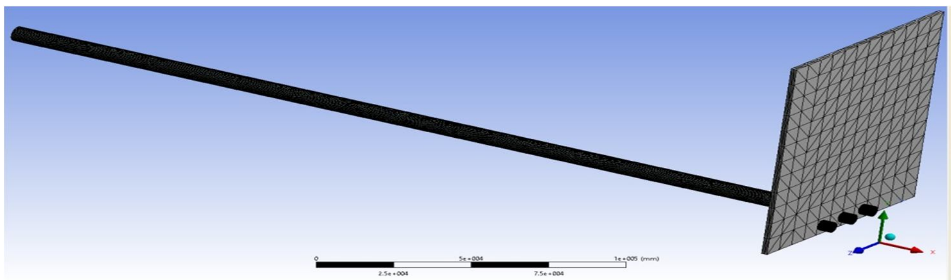

Fig. 5 Meshing of Surge Tank

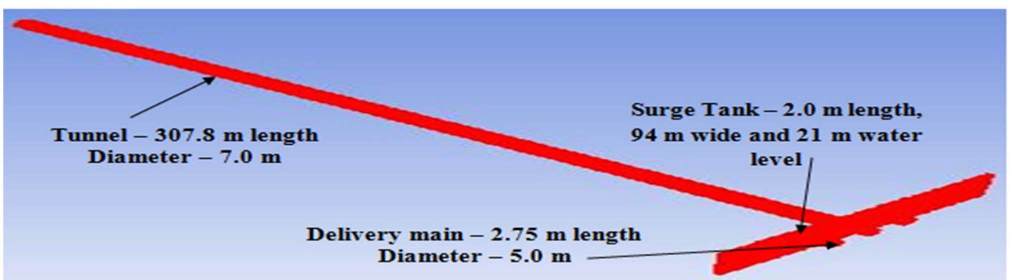

Fig. 6 Patched Water Level

The peak surge height was estimated by means of User Defined Function written in C-Programming. The results were evaluated by solving the basic governing equations of two-equation type turbulence models. For the two-dimensional steady state incompressible flow, the Reynolds-Averaged Navier-Stokes equations are given below [7].

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots.. (6)$$

$$\rho\left(\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y}\right) = -\frac{\partial \bar{p}}{\partial x} + \frac{\partial}{\partial x}\left(\mu\frac{\partial \bar{u}}{\partial x} - \rho u'u'\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{u}}{\partial y} - \rho u'v'\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\rho\left(\bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y}\right) = -\frac{\partial \bar{p}}{\partial y} + \frac{\partial}{\partial x}\left(\mu\frac{\partial \bar{v}}{\partial x} - \rho u'v'\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{v}}{\partial y} - \rho v'v'\right) \quad \ldots\ldots\ldots\ldots... (8)$$

In the eq. (7) & (8), the terms $-\rho u'u'$, $-\rho v'v'$ and $-\rho u'v'$ behave like stress terms, the first two terms are normal stresses and the last term is a shear stress [8].The mean of all the extracted values was evaluated to obtain the values of surge height for the unsteady conditions by means k-epsilon and k-omega turbulence models as highlighted in Table 2. The plots depicting the pressure oscillations for all the three cases are detailed from Fig. 7 (a) to (c). Further, the simulation analysis is extended to check the flow distribution in the Surge by adopting 1/10 of the approach tunnel length. However, the full-length model results were in harmony with the analytical values at different time steps.

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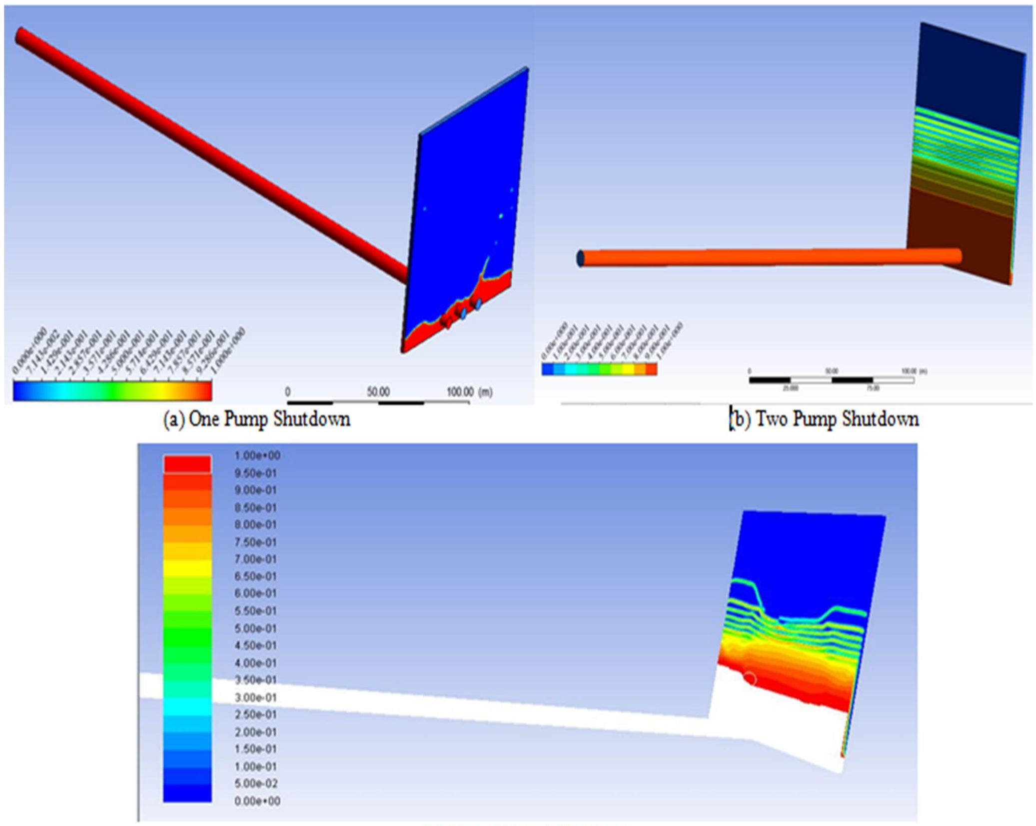
Volume 10 Issue II Feb 2022- Available at www.ijraset.com

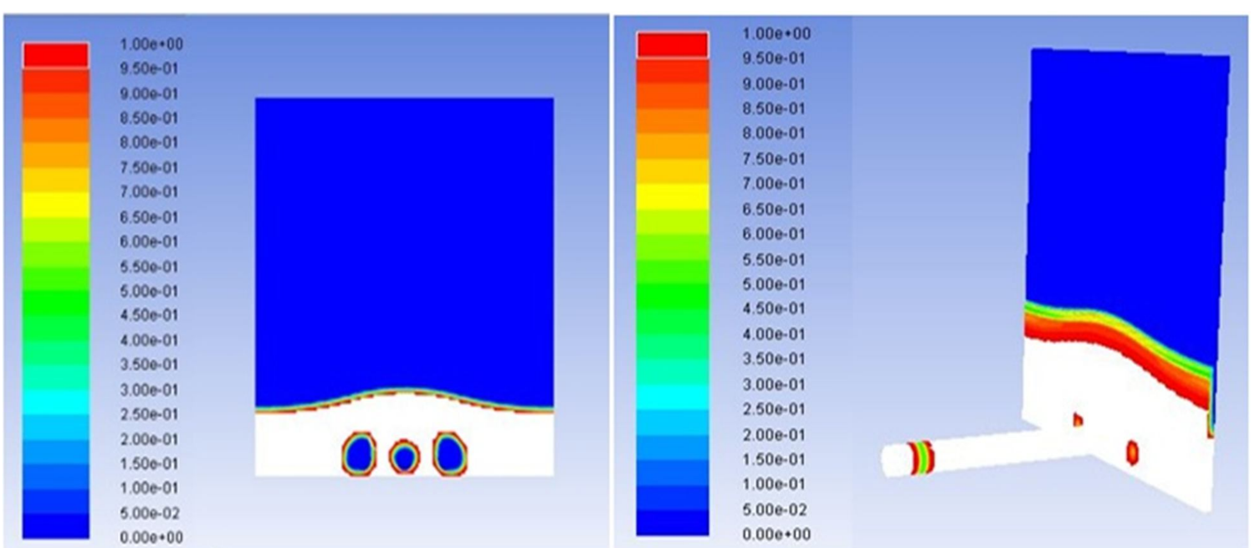
Whereas, the reduced model length results were not in corroboration with analytical estimates at the same time steps. A plot depicting the above two approaches for three pump shutdown is shown in Fig. 8.Furthermore, it was also observed that in case of reduced model length studies the liquid level in the surge tank was dropping below the Minimum Draw Down Level (MDDL) to be maintained. As a consequence of this, air entrainment occurring close to pumps could be seen from the enclosed volume fraction figure appended herewith in Fig. 8. Therefore, it was decided to include the full length of the approach tunnel to the surge tank in the simulation studies.



(a) One Pump Shutdown (b) Two Pump Shutdown

(c) Three Pumps Shutdown

Fig. 7 Contours of Volume Fraction



(a) (b)

Fig. 8 Curtailed lengthsimulations (3-pump shutdown)

IV. RESULTS AND CONCLUSIONS

From the present study, the following results were deduced from analytical and simulation analysis.

1) The significant parameters were estimated analytically as detailed in Table 2.

TABLE 2
RESULTS OF ANALYTICAL CALCULATIONS

Description of the Parameters	Evaluated values		
Reynolds number of tunnel	16.743×10^{6}		
Friction factor of tunnel material	0.00755		
Reynolds number of delivery main	4.688×10^{6}		
Friction factor of the delivery main	0.009071		
Peak upsurge height (m)	One-Pump Shutdown	Two-Pumps Shutdown	Three-Pumps Shutdown
	0.471	0.862	1.493
Total Periodic Time of Oscillations (T_p) (s)	112	80	65

2) The simulated results of peak surge height for different conditions of unsteady flow were analyzed using ANSYS – Fluent by means of user-defined function. A macro was generated based on the VOF - multiphase analysis to quantify the surge height as detailed in the Table 3 below.

TABLE 3
Simulation Results Of Peak Upsurge

Unsteady Flow Condition	Simulated Peak upsurge height (m)	
	k-ε model	k-ω model
One-Pump Shutdown	0.4556	0.4523
Two-Pumps Shutdown	0.866	0.872
Three-Pumps Shutdown	1.499	1.507

3) The simulation results obtained from the turbulence models via., k-ε and k-ω turbulence models were observed to be in good consonance with analytical estimations as detailed in the Fig. 8.

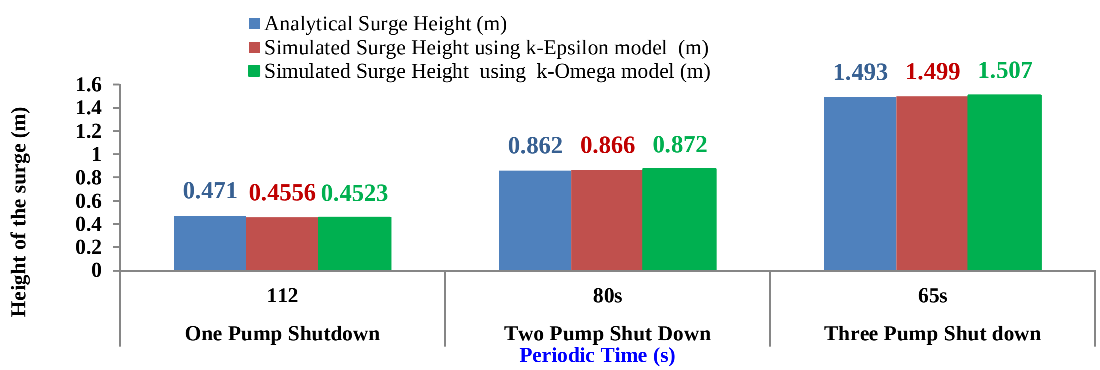


Fig.8 Comparative Results of Peak Surge Height

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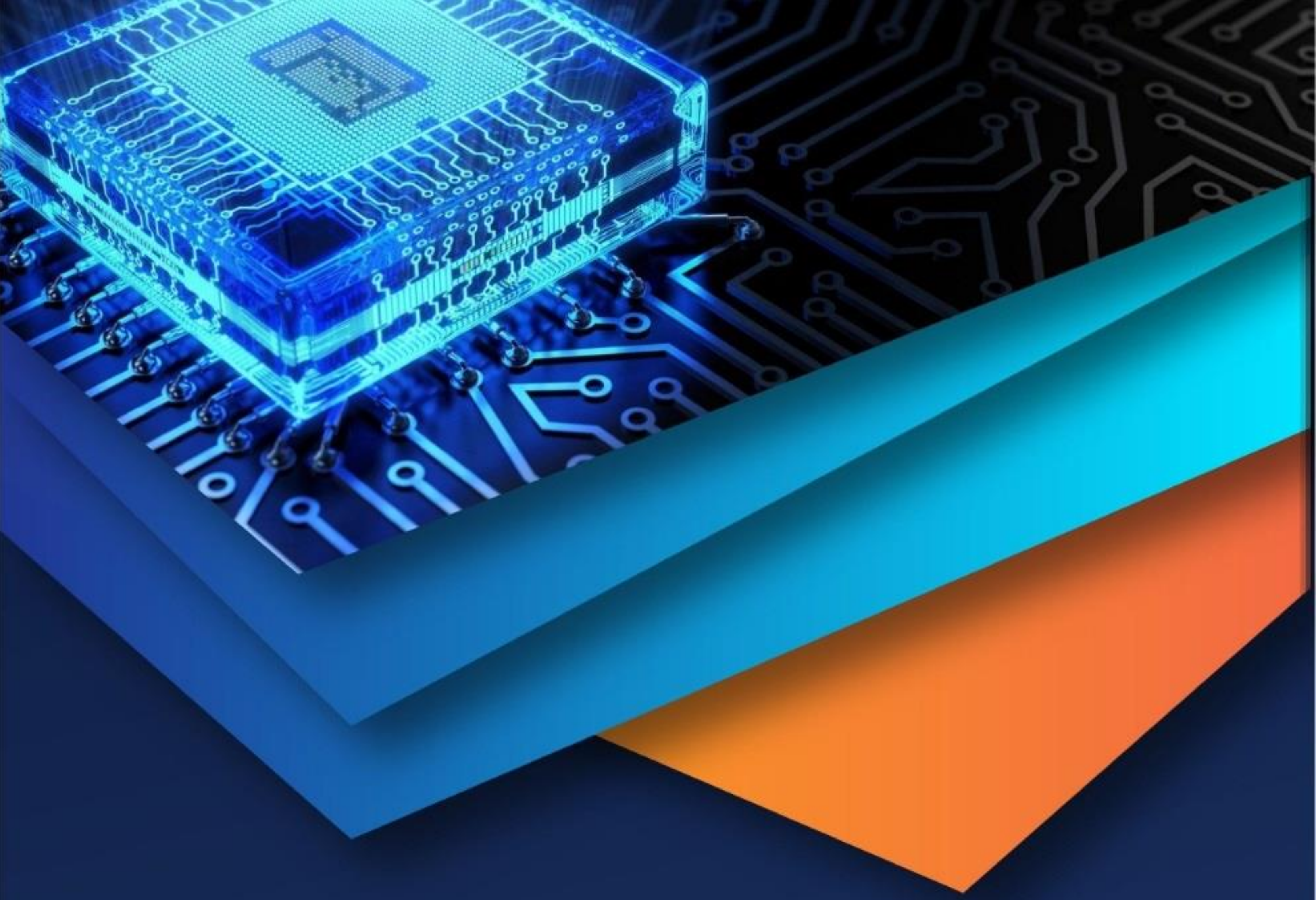

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