Study to Predict Blast Load on Structure due to the Explosion of an EHV Power Transformer Using Computational Fluid Dynamics (CFD) based Approach

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Abstract: Extra High-voltage power transformers are critical to the electrical infrastructure because they allow for the efficient transfer of power over huge networks. Arcing is the main cause of transformer explosions and fires. The previous work provides a method for evaluating and calculating arc energy and peak overpressure inside the HV Transformer tank owing to electrical failures, which is then used as input for CFD simulation. Computational Fluid Dynamics (CFD) provides a robust numerical approach to modelling blast wave propagation and its interaction with structures. This minimizes the need for full-scale testing by lowering the overall effort and cost of experimentation and data collection.
This paper lays the groundwork for a comprehensive analysis & structural design of a 500MVA transformer compound RC firewalls open to the sky subjected to an internal explosion. Using ANSYS Fluent, a CFD simulation is conducted to model blast wave propagation, capturing pressure and temperature variations over time. This Fluid-Structure Interaction (FSI) approach offers critical insights into the structural integrity of blast barriers, aiding in the design of more resilient protection systems. By leveraging CFD-based numerical simulations, key blast parameters such as Incident pressure (P_{so}), Reflected pressure (P_r), Wave arrival time (t_a), and positive and negative phase durations (t_o, t_o’), Blast Impulse (I), and Temperature are extracted, analyzed, and compared with the results produced with the TNT-based empirical method. The time-dependent blast load data pave the way for mapping in ANSYS Transient Structural, where the deformation and failure analysis of the transformer blast protection walls will be studied.

Key Words: CFD; Explosion; Blast-Force; Incident & Reflected Pressure; TNT

Introduction

EHV transformers (132 kV to 500 kV) are used to step up or down the voltage in power transmission. They work using electromagnetic induction, where AC in the primary coil creates a magnetic field that induces a voltage in the secondary coil. Transformer oil is used for cooling and insulation, helping prevent electrical discharge, maintaining dielectric strength, and removing heat generated. HV Power Transformers rank among the most hazardous electrical devices due to their substantial oil content, which is in close proximity to components operating at high voltages. This combination of oil and high-voltage elements creates a significant safety risk, making these transformers particularly dangerous within electrical systems (Petersen et al., 2013). Internal Arc caused by a fault in the Electrical system is the predominant source of Transformer Tank Rupture & thereby, Explosion.

These explosions generate intense blast waves capable of inflicting severe structural damage. To mitigate collateral damage associated with these explosions, EHV transformers are enclosed within blast protection walls, typically made of reinforced concrete. These walls serve to contain high-pressure shock waves, prevent the spread of fire, and safeguard nearby equipment and personnel from structural damage due to blast impact. The effectiveness of these barriers is crucial in ensuring the safety of substations, power stations, and industrial facilities handling high-voltage power systems. A study (Ranganekar, R. 2024) Confirmed a strong correlation between Electrical faults and Explosion, followed by fire in HV transformers. This Study (Ranganekar, R. 2024) Provides a tool to standardize Arc Energy & Peak overpressure inside the HV Transformer tank in the Electrical Network due to electrical faults. Utilizing Arc Energy (E_{arc}) & Tank's internal pressure (P_s) will facilitate Structural Designers to perform Dynamic Analysis of Blast Resistant Structures by using various methods like Empirical (or analytical) methods, Semi-empirical methods, & Numerical methods (CFD).

Traditional empirical methods for estimating blast loads may lack precision when applied to complex environments. CFD offers a powerful tool for simulating the physical phenomena associated with blast waves, allowing for a detailed assessment of the resulting structural loads. These include more precise estimates of the blast wave's energy and resulting pressure. This paper explores the application of CFD in modelling blast waves originating from transformer explosions, evaluating their impact on Transformer compound RC Fire/Blast Walls, and providing mitigation strategies. The computational software Workbench ANSYS FLUENT is used for Fluid-Structure Interaction in this research for CFD Analysis, which will derive the Time History Response of wave pressure, incident (Pso), and reflected pressure (P_r), Incident Blast Pressure with time of Arrival (t_a), Capture Positive Phase (t_o) & Negative Phase duration (t_o') for reflected pressure. The structural response is studied using Workbench ANSYS Transient Structural with MODAL Analysis, which includes deformation and maximum principal stress in concrete. The simulation model consists of a 500MVA Transformer Bay surrounded by a rectangular geometric configuration. Cast in situ RC Blast Wall on three sides (Side & Rear), with the front open (with steel fence) and open to the sky. The results for shock wave incident overpressure(P_{so}) and reflected Pressure (P_r) were compared with empirical predictions of authors, for example, Kingery-Bulmash curves, Surface Burst (Karlos & Solomos, 2013) & Mills' Empirical. The results enable a comprehensive analysis of shock wave propagation in complex environments and their interaction with concrete firewalls.

Comparatives of Work Done Earlier & Numerical Simulation:

Flood et al. (2010) [4] provided a fast, accurate, and versatile method of simulating the propagation of a blast wave within complex built environments. An alternative method proposed here is to use a simulation approach implemented within a coarse spatial and time framework, where the mesh elements and time steps are orders of magnitude larger than those used in conventional CFD simulations. This reduces computational load & executes faster than conventional CFD simulations. C. Daiz-Ovalle, A. Lopez-Molina & R. Vazquez-Roman, [6]"A CFD based Approach to Predict Explosion Overpressure: A Comparison to Current Methods", Chem. Biochem Eng. Q.30 (4) 419-427, 2016. A CFD-based approach has been developed in this work to predict the overpressure produced during an explosion. An adiabatic exothermal reaction allows computing the explosion energy release. To validate the proposed CFD approach, overpressure predictions' based on this methodology are compared with results produced with the TNO-based method. The CFD simulations were carried out in the ANSYS CFX tool. This description corresponds to a cycle of power generation, which is characteristic of an explosion.

Arif S.M. Sohaimi, M.S. Risby, Saiddi A.F.M. Ishak, Khalis S, M.N. Norazman, Ariffin. I, M.A. Yusof [7]"Using CFD for Blast wave Propagation under Structure", ICCS 2016 (International Conference on Computational Science), explored using CFD for Blast wave Propagation under Structures using ANSYS software. Full-scale blast tests are expensive and time-consuming, but by using computational-based numerical simulations, they can virtually predict these wave propagations and minimize the need for experimental testing. This paper presents two different blast analyses: free field air blast and blast loading towards a structure using ANSYS FLUENT software. The computed results were found to be in agreement with theoretical & additional experimental data. The verified free field blast model was expanded to study the blast loading response towards a structure.

L. COSTA NETO, G. N. DOZ, [8] "Study of blast wave overpressures using computational fluid dynamics". This paper presents an assessment of blast wave overpressures using computational fluid dynamics software. Analyses of phenomena, such as reflection of shock waves and channeling effects, were done. The results suggest that standard analytical predictions aren't accurate enough for overpressure analysis at short stand-off distances, and that poorly designed buildings may amplify shock-wave overpressures due to multiple blast-wave reflections, thereby increasing the destructive potential of the explosions.

A detailed 3D engineering analysis is needed to estimate the pressure waves and impacts generated by transformer blasts, providing accurate inputs for the structural design of firewalls and blast walls. Figure 1 shows a graphical flow chart of the proposed methodology.

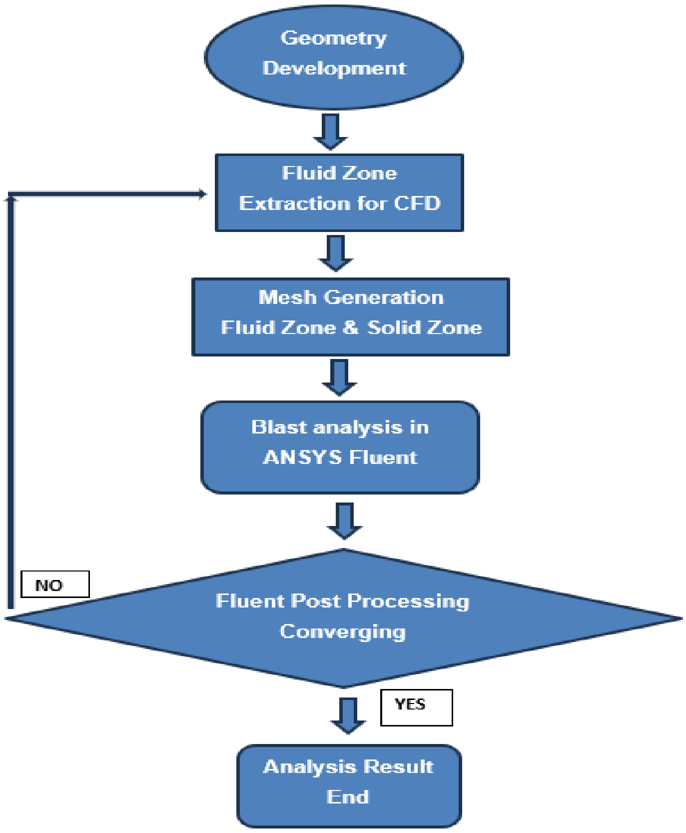


Figure 1: Graphical Flow-Chart (Source: Compiled by author)

Research Gap:

All available research papers and technical literature are based on specific explosive types, such as TNT, C4, RDX, PETN, ANFO, etc., with assumed charge weights and standoff distances. Limited research explicitly addresses the prediction of Blast Energy due to an EHV Transformer explosion. Lack of open-source experimental data for HV transformer blast events. Limited integration of arc flash and combustion models into FSI simulations. Need for high-fidelity multi-physics simulations combining thermal, chemical, and structural aspects.

Problem Statement:

Most research papers and technical literature available are based on specific explosive types, such as TNT, C4, RDX, PETN, and ANFO, with assumed charge weights and standoff distances. For convenience, however, it is general practice to express the basic explosive input or charge weight W as an equivalent mass of TNT (Karlos & Solomos, 2013). W_{TNT} (Equivalent Mass of TNT) is used to derive Scale distance as given by Hopkinson–Cranz law. Scaling laws provide parametric correlations between a particular explosion and a standard charge of the same substance. Various Imperial Methods, as listed below, are used to predict Blast Pressure on the structure.

Kinney, Brode's Equations (1955), Newmark & Hansen (1961), Mills (1987), Kingery & Bulmash Equations, UFC 3-340-02 (Unified Facilities Criteria – Structures to Resist the Effects of Accidental Explosions), TM5-1300 (Structures to Resist the Effects of Accidental Explosions) Henrych's Empirical Relations CONWEP (Conventional Weapons Effects Program) are empirical method use to predict blast pressure. These Models are based on assumed charge weights and standoff distance and do not consider the effect of obstacles in the Explosion. In contrast, CFD simulation considers local environmental factors such as congestion, confinement, and blockages [7]. None of the Transformer manufacturers provides estimated Arc Energy and blast overpressure likely to develop in the transformer tank due to an explosion in their technical data sheets. The challenge of predicting and evaluating blast energy or burst pressure resulting from HV power transformer explosions is addressed in the research study (Ranganekar, R. 2024). Furthermore, there are no international code provisions or industrial standards for calculating Incident Pressure (P_{so}) and Reflected Pressure (P_r) on the structure due to transformer explosions, which can be used for designing blast-resistant structures surrounding HV Power Transformers in the substation/Power Station complex.

1.1. Transformer Explosion & Rectangular Geometry Description

The Arc Energy & Peak Overpressure generated inside the HV Transformer tank during the event of the Explosion are presented below (Ranganekar, R. 2024)[1] for 500MVA TXF-1: **Arc Energy E_{arc} = 32.1 MJ & P_s = calculated tank pressure [kPa above atmospheric] = 701.90 kPa Absolute pressure @ temperature 300^0C to 700^0C.**

The 3D Model had been generated for the 500MVA Transformer manufacturer by GE as shown in figure 2. As per vendor Input, the Transformer Tank, Radiator, and structural geometry are as described below:

Table 1: Architectural & Structural Dimensions (Source: Compiled by author)

Architectural Dimension				Structural Element Property		
Length/ Depth (m)	**Rear Wall Width (m)**	**Oil Catchment Depth (m)**	**Height of Shear Wall Above Plinth (m)**	**Base Raft THK (mm)**	**Wall THK Below Plinth (mm)**	**Wall THK Above Plinth (mm)**
17.92	22.00	1.95	10.00	900	400	400/300

Table 2: Equipment Clearance & Dimensions (Source: Compiled by author)

Clearance Dimension		TXF Concrete Plinth Dimension		TXF Steel Tank Dimension		
Distance of Rear Wall from TXF Plinth (m)	**Distance of Side Wall from TXF Plinth (m)**	**L (m)**	**B (m)**	**L (m)**	**B (m)**	**H (m)**
3.630	5.265	11.685	4.66	12.6	4.635	4.077

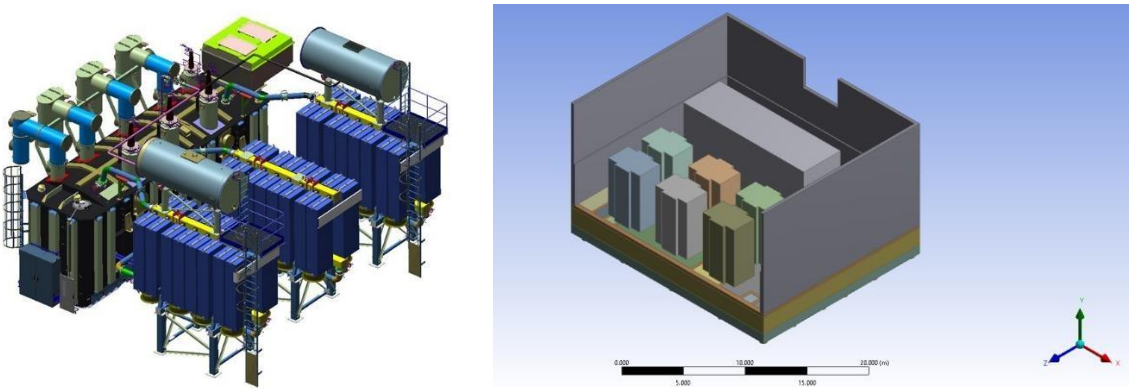


Figure 2: 3D Arrangement of Transformer Tank, Radiator & Ansys Geometry Model (Source: Compiled by author)

Rectangular Geometrical Dimensions of the 500MVA HV Transformer compound for GE are extracted from OEL, Structural GA Drawings, and Architectural drawings. Transformer steel Tank clearance from the Rear and side Blast/firewall, or the Clear Distance of the Rear Wall/side wall from the TXF Plinth (m), is maintained as per the vendor OEL drawings. This clearance of the steel tank/Plinth from the Rear/Side wall is considered the Ground Stand-Off Distance in structural Blast analysis. The dimensions of the transformer tank and reactor, the total mass of the transformer, the oil mass, the type of oil, and the oil volume are extracted from these technical data sheets, which are essential inputs for the CFD Simulation.

A 500MVA EHV transformer reinforced concrete compound (Rectangular configuration) with a pile foundation as a substructure and a cantilever vertical RC shear wall/ blast wall/firewall as a superstructure open to the sky is modelled & analyzed to assess the impact of an internal explosion on its surrounding protective structures. The model considers all obstacles, such as exciter transformers, tanks, radiators, steel grating with gravel, and walls. The geometrical configuration and dimensions of structural elements such as Pile Diameter and spacing, Base Pile Raft thickness, Transformer Plinth Size, Radiator Plinth Size, Rear Blast wall thickness and height, Side Blast wall and height, as per vendor Structural Arrangement data and drawings.

1.1. Fluid Zone, Mesh & Material Properties:

The fluid zone is a crucial region that encompasses the fluid (gas, vapor, or mixture) involved in the explosion. It serves as the domain in which key phenomena such as shockwave propagation, temperature and pressure changes, and fluid dynamics are modelled. The behavior of the fluid zone determines how the explosion unfolds, how pressure waves travel, and how surrounding structures are affected by the blast. The Polyhexa core mesh in ANSYS Fluent is an advanced hybrid mesh that combines the advantages of hexahedral and polyhedral cells. Assign air properties for the fluid domain and concrete properties for the walls. Set a fine time step of 100ms to capture the transient shockwave accurately.

Table 3A: Fluid region mesh (Source: Compiled by author)

Domain	No. of elements	No. of nodes	Types of elements
Fluid	820941	1422285	Polyhexcore
Solid	892782	2743539	Tri & Quad

Table 3B: Fluid Material properties (Source: Compiled by author)

Fluid material	Molecular weight (kg/kmol)	Viscosity (kg/m2)	Density
Air - Ideal gas	28.966	1.7894e-5	Ideal Gas Law

Table 4: Solid material properties (Source: Compiled by author)

Material Name	Density (kg/m3)	Tensile ultimate strength (Mpa)	Compressive ultimate strength (Mpa)	Poisson Ratio	Modulus of Elasticity (Mpa)	Shear Modulus (Mpa)
Concrete Grade C40	2500	3.2	32	0.2	26,587.21	12,385.42
Structural steel Fe460	7850	460	-	0.3	2e+5	7.6923e+10
Gravel	2000	-	-	0.4	80	-

1.2. Boundary Conditions & Assumptions:

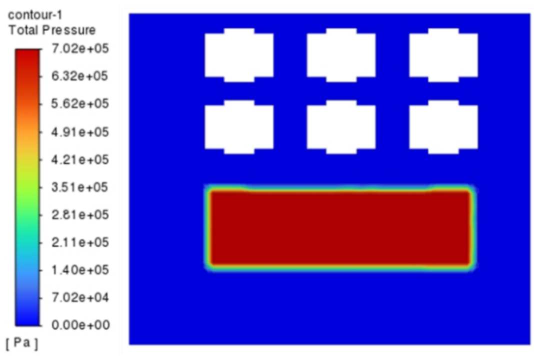
The Blast Pressure and temperature are based on a 500MVA TXF, structural piles at the bottom of the raft, a total of 47 piles, 600mm diameter, modelled as pinned supports. Assumptions follow:

a) Heat transfer (conduction, convection, radiation) and non-isothermal effects were ignored.
b) Chemical reactions and mass transfer were ignored. Gravity effects were ignored.
c) Turbulence effects are ignored as the pressure wave is generated by an external means, and its propagation through air is unaffected by turbulence.
d) The projection of material from the explosion into the air was not taken into account.

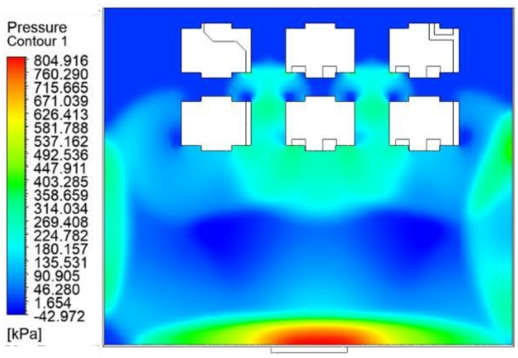
e) Fluid-Structure Interaction (FSI): One-way coupling is assumed; the fluid (air and explosion gases) impacts the wall, but wall deformation does not affect fluid flow.
f) Reflection Effects: The wave reflects off the walls, amplifying the loads on the structure.
g) Negligible Influence of Wall Deformation on Fluid Flow: Wall deformation is small and does not significantly alter fluid behaviors.
h) All obstacles (like exciter transformers, radiators, and walls) and all other structures are considered Non-Slip adiabatic walls.

ANSYS Fluent, a Computational Fluid Dynamics (CFD) simulation [6], is used to model blast wave propagation and analyze fluid-structure interaction (FSI). A CFD-based numerical simulation will be conducted to analyze the blast wave characteristics and their impact on the RC structure of the 500MVA EHV Transformer Compound. The time-dependent blast load data is then mapped to ANSYS Transient Structural, where the deformation and failure analysis of the transformer blast protection walls are evaluated. CFD Results will be compared with the empirical method using Kingery-Bulmash curves for Surface Burst (Karlos & Solomos, 2013).

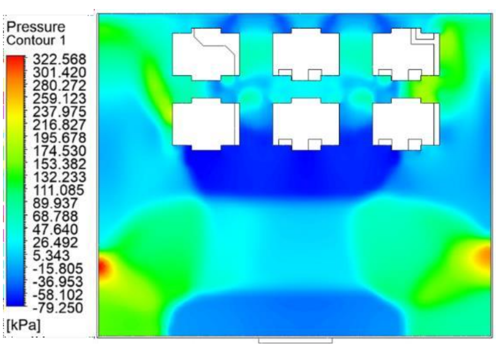
Results and Discussion:



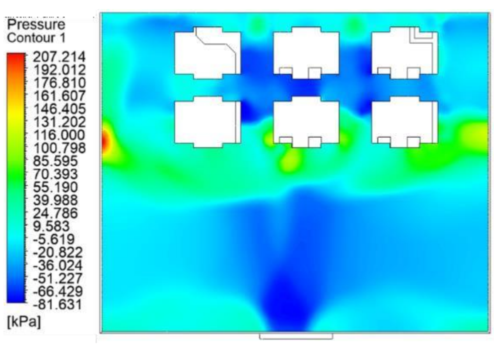
0ms



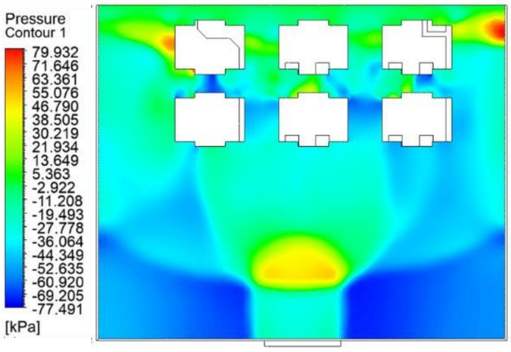
10ms



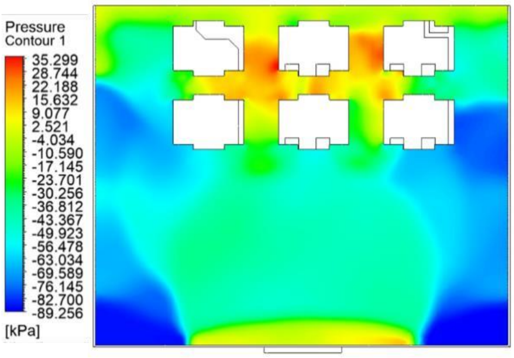
20ms



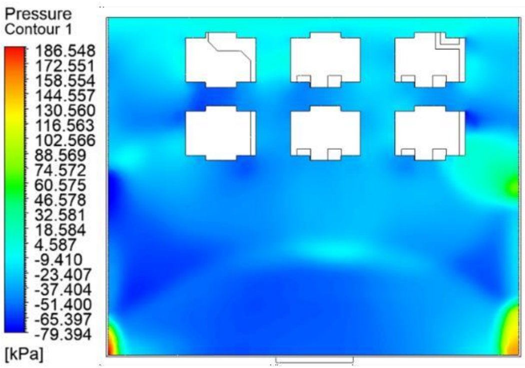
30ms



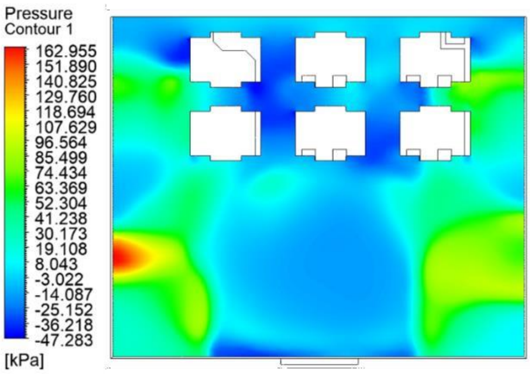
40ms



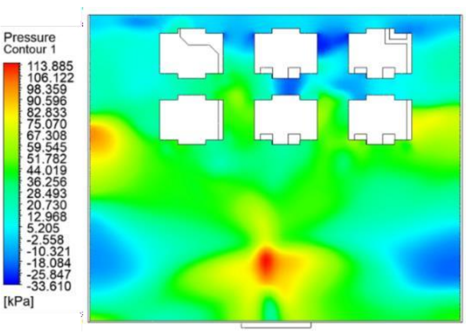
50ms



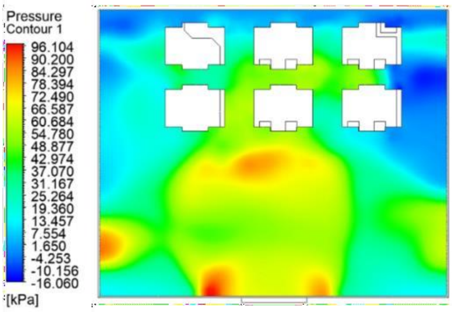
60ms



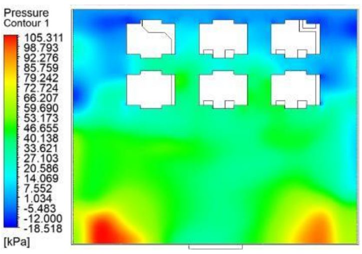
70ms



80ms

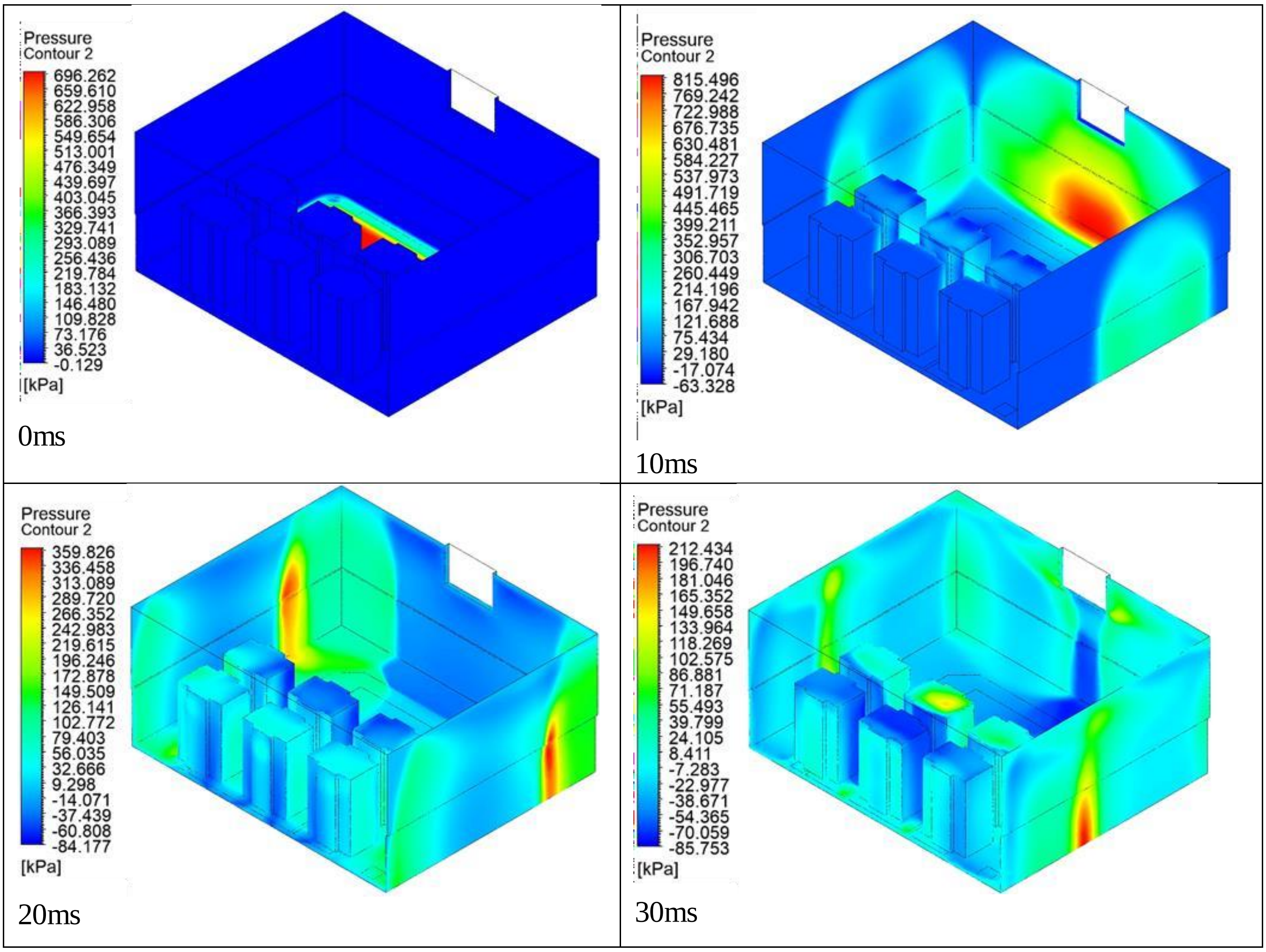


90ms



100ms

Figure 3: Transformer Blast Pressure contour on XY-plane @ Plinth Level (Source: Compiled by author)



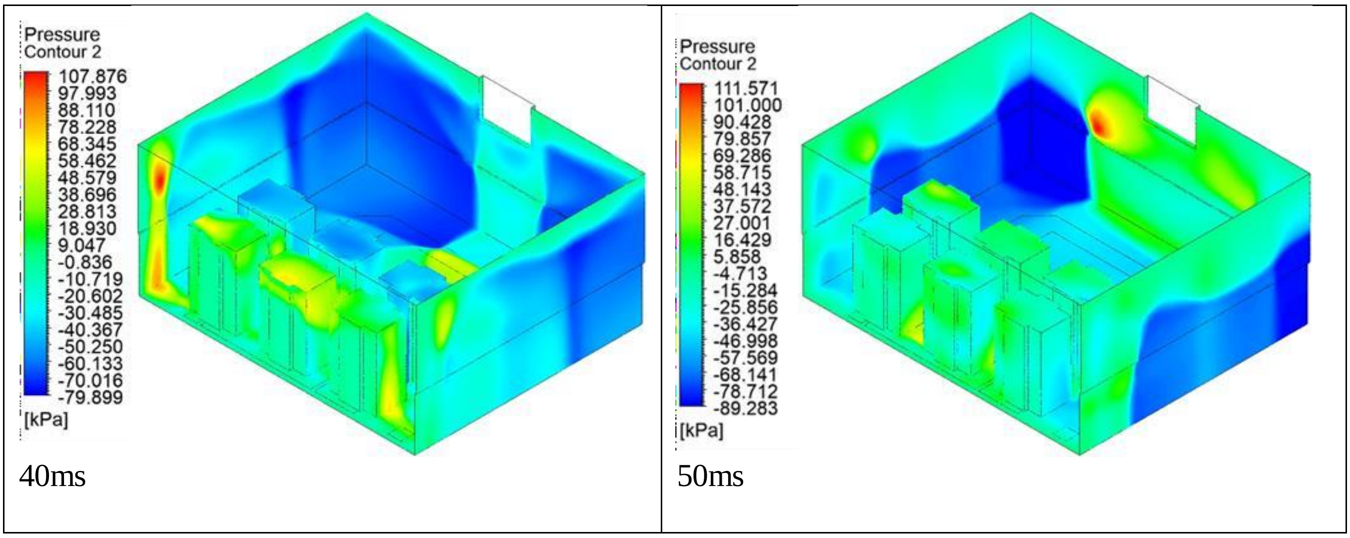
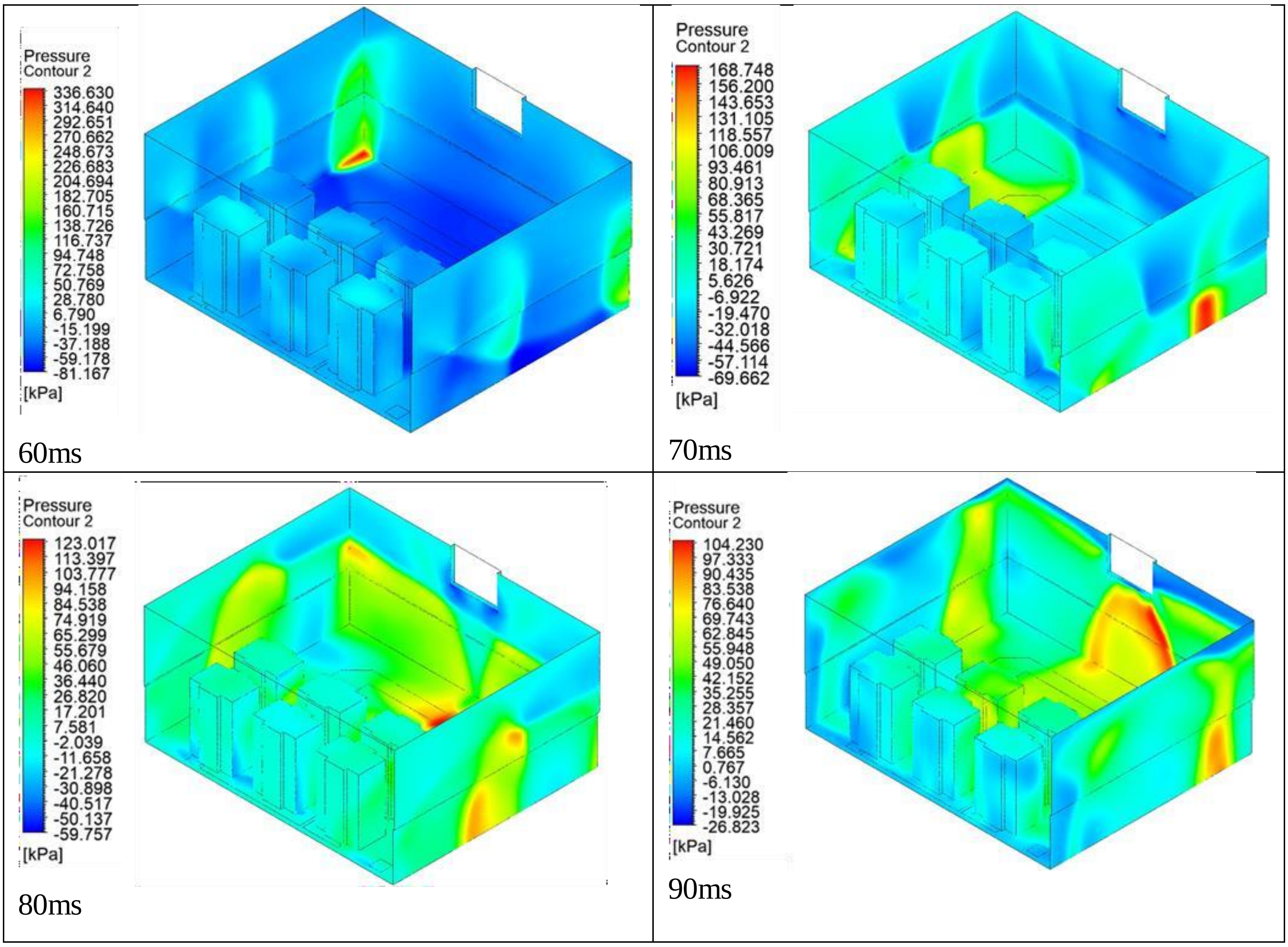


Figure 4: Wall Pressure contour on 3D-plane (Source: Compiled by author)



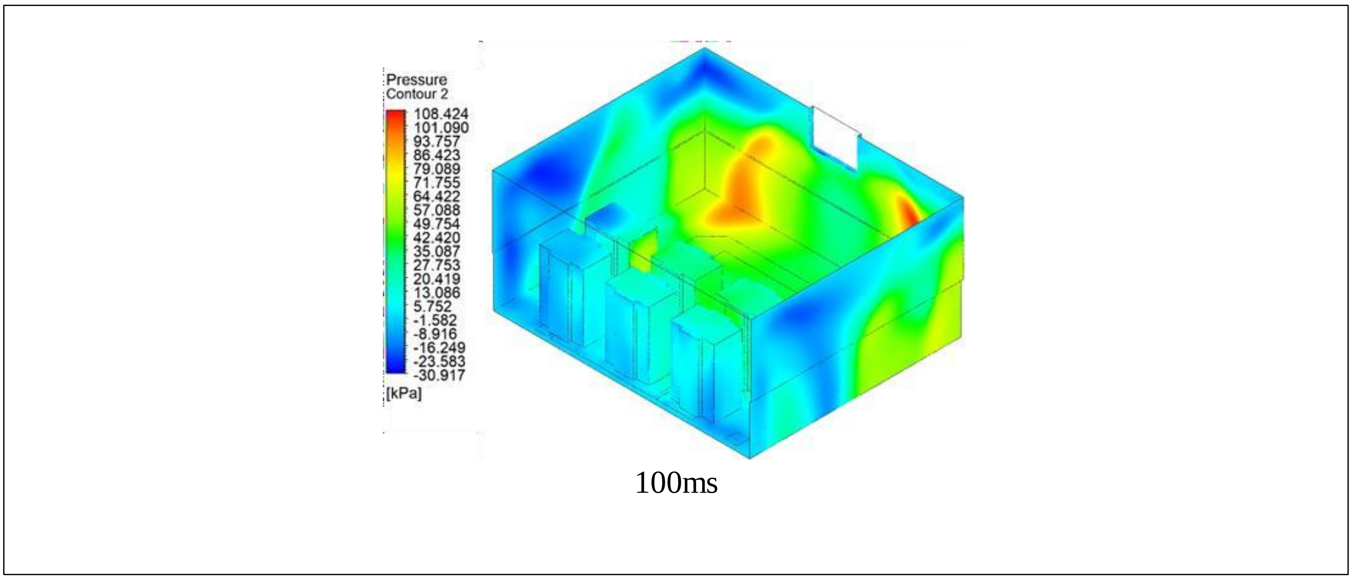


Figure 5: Wall Pressure contour on 3D-plane (Source: Compiled by author)

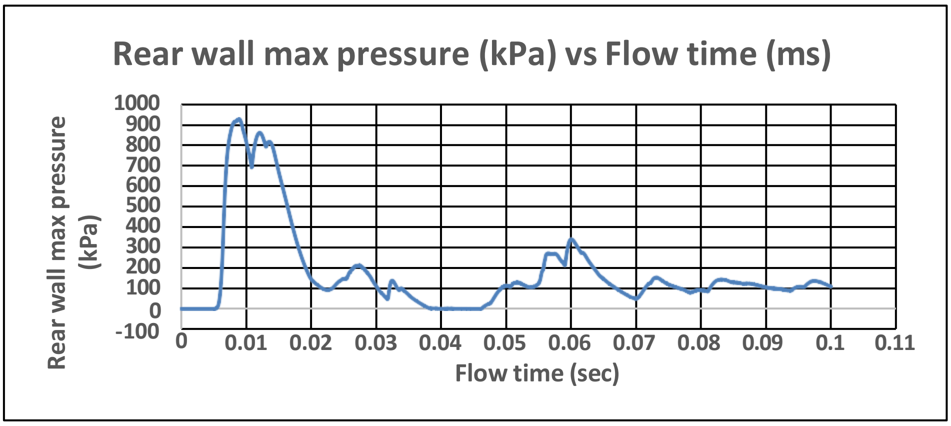


Figure 6: Time-History for Rear Wall (Gauge Pressure) (Source: Compiled by author)

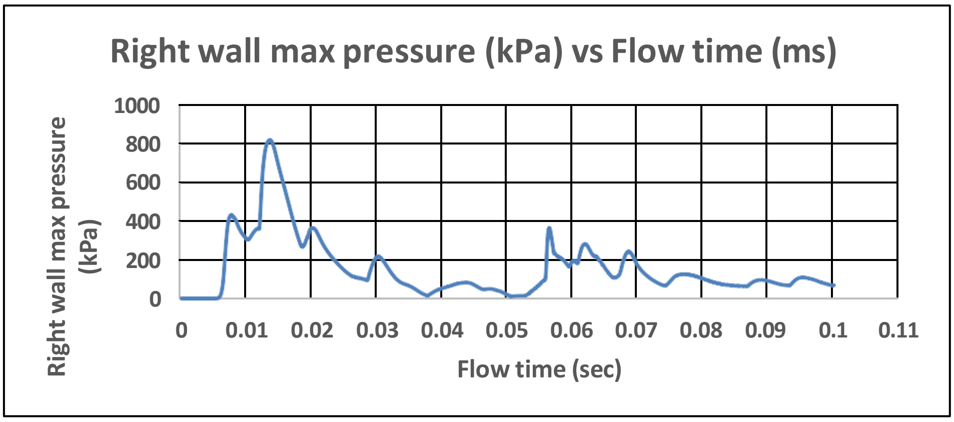


Figure 7: Time-History for Right Wall (Gauge Pressure) (Source: Compiled by author)

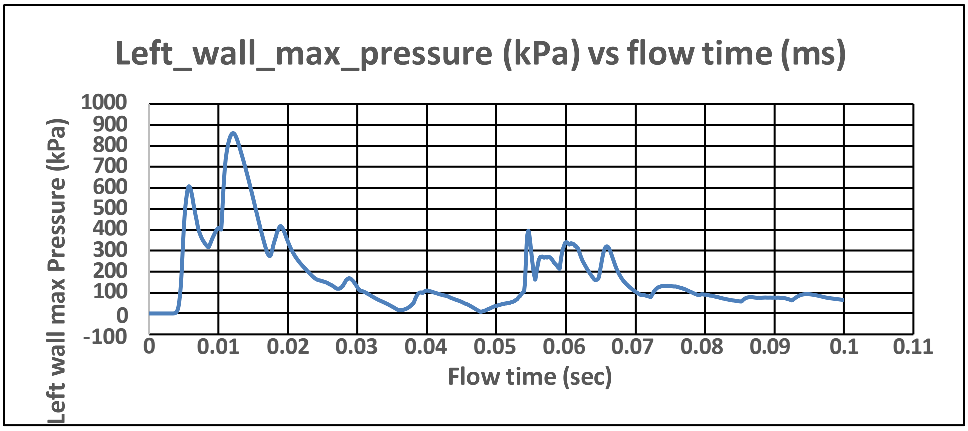


Figure 8: Time-History for Left Wall (Gauge Pressure) (Source: Compiled by author)

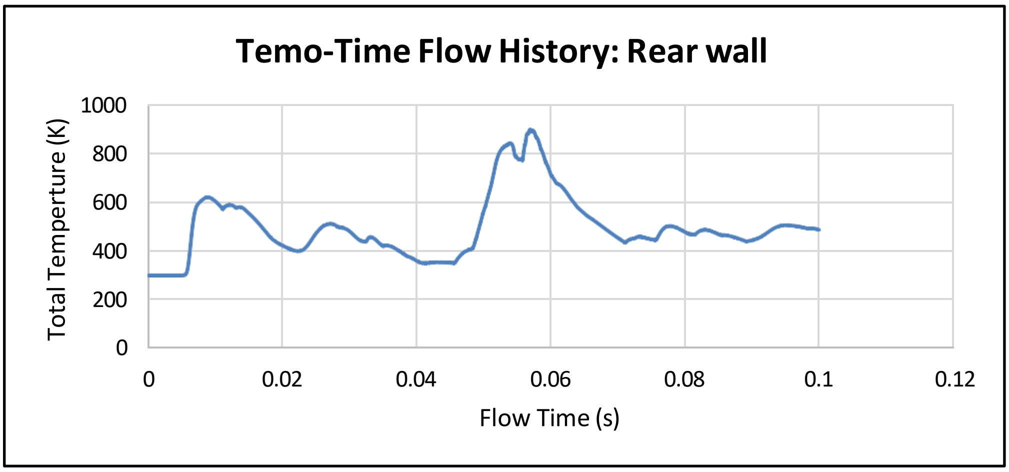


Figure 9: Temperature-Time Flow History for Rear Wall

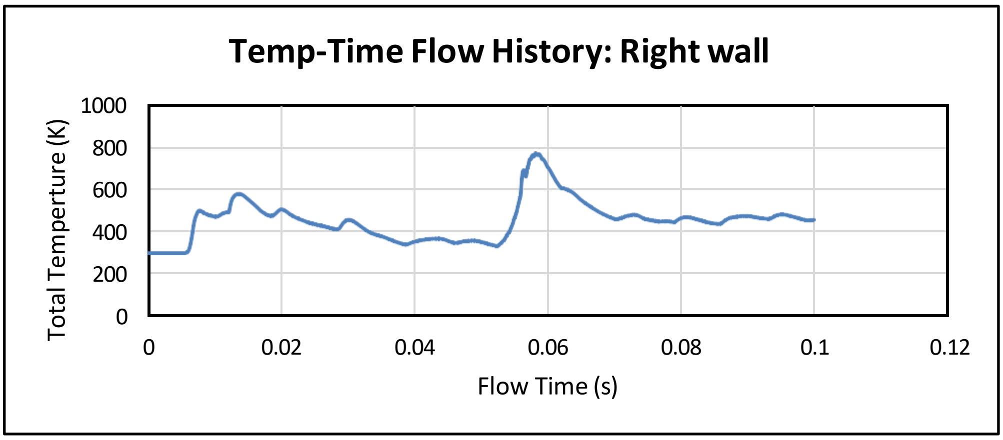


Figure 10: Temperature-Time Flow History for Right Side Wall

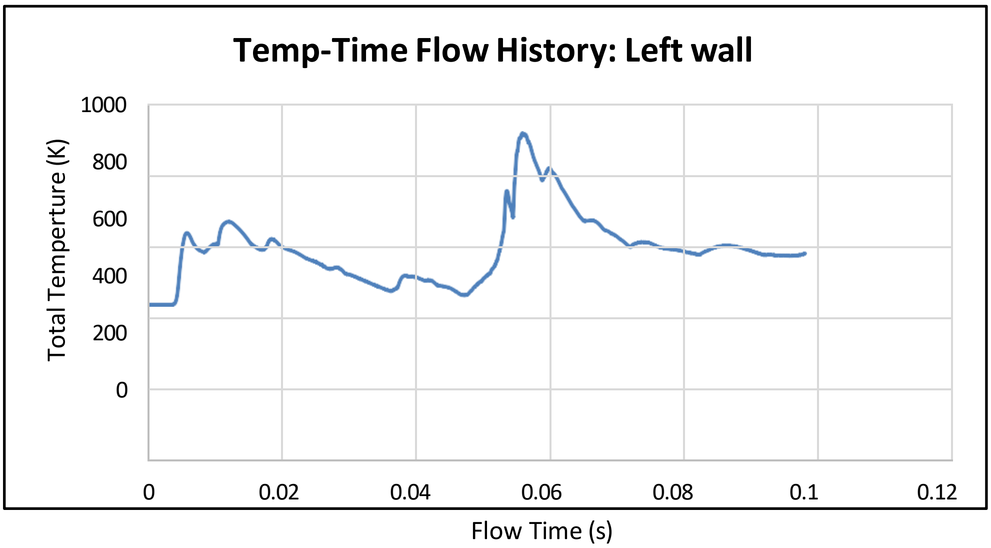


Figure 11: Temperature-Time Flow History for Left Side Wall

Create a probe & line on three walls for incident, reflected pressure (average pressure).

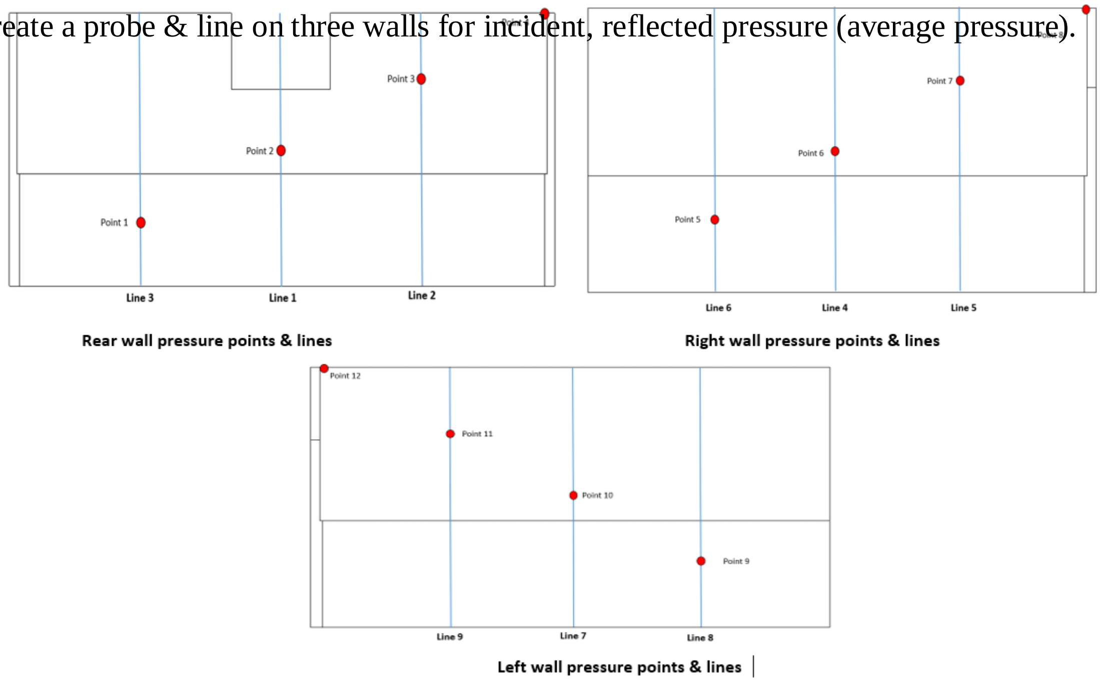
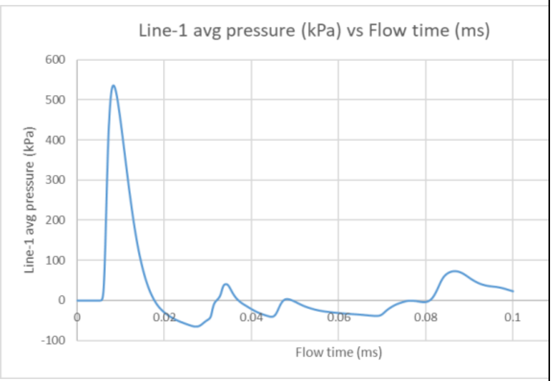
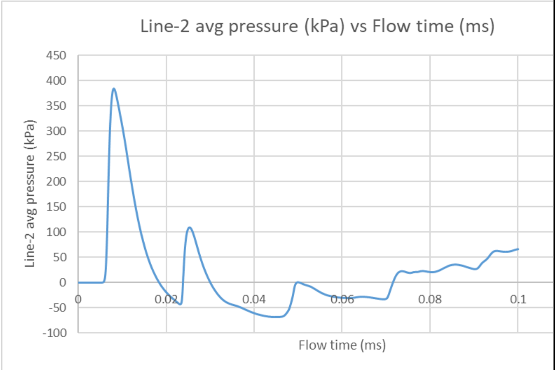


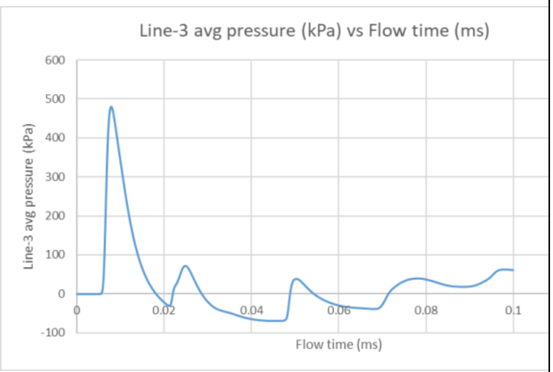
Figure 12: Probes & Lines



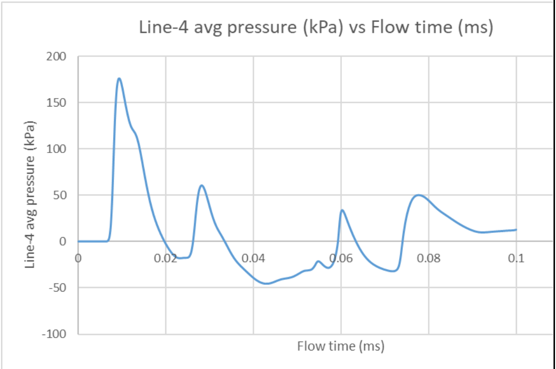
At Line-1



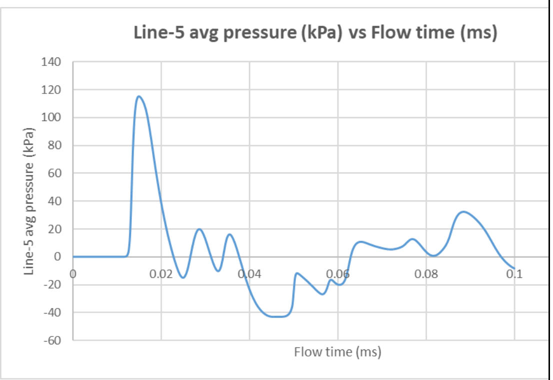
At Line-2



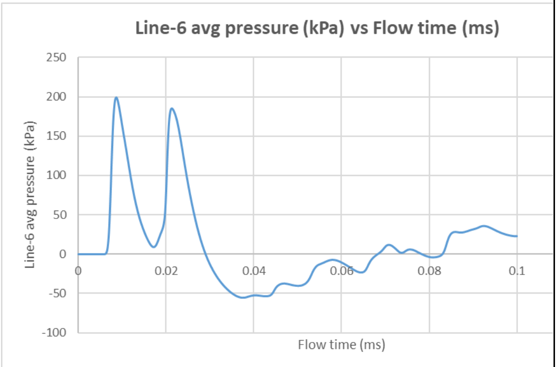
At Line-3



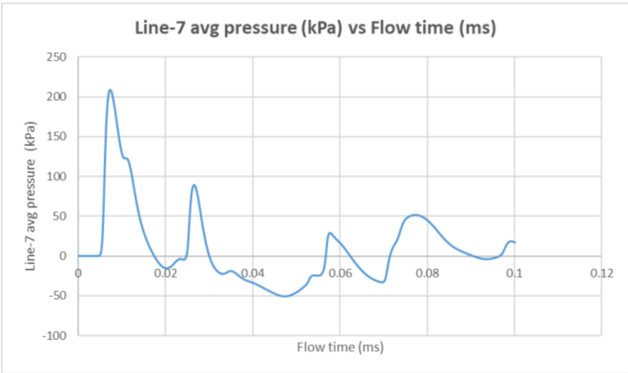
At Line-4



At Line-5



At Line-6



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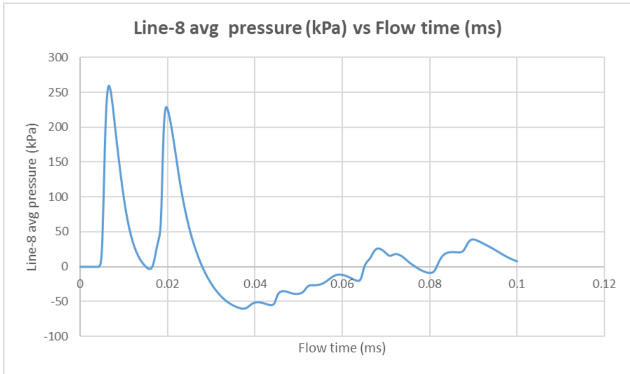
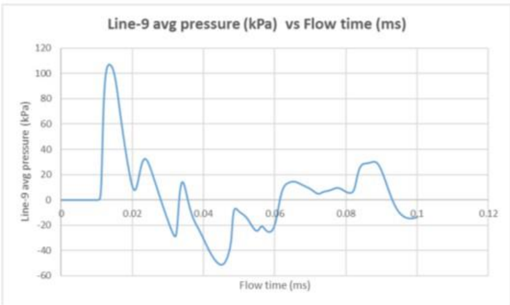


At Line-8



At Line-9

Figure 13: Average Reflected Pressure Vs Time on Probes

From Contours Figure No. 4:

- Maximum +ve Transformer Blast Pressure = + 804.916 kPa @ 10ms
- Maximum -ve Transformer Blast Pressure = -89.256 kPa @ 50ms

From Contours Figure No. 5 & Time-History Figures 6, 7 & 8:

❖ **FSI on Rear Wall:**

- Maximum Reflected Blast Pressure (P_r) on Rear Wall = + 910.00 kPa @ 8ms
- Maximum Incident Blast Pressure (P_{so}) on Rear Wall = Cannot Capture
- Time of Arrival (t_A) = 6 ms
- Positive Phase Duration t_{O1} = 38-6 = 32 ms
- Positive Phase Duration tO2 = 100-38 = 62 ms
- Blast Impulse (I): 17.970 Kpa-sec
- Maximum Temperature Rear Wall subjected = + 900 K (626.85^0 C) @ 57ms

❖ **FSI on Right Wall:**

- Maximum Reflected Blast Pressure (P_r) on Right Wall = + 805.00 kPa @ 14ms
- Maximum Incident Blast Pressure (P_{so}) on Right Wall = + 410 Kpa @ 8ms
- Time of Arrival (t_A) = 7 ms
- Positive Phase Duration t_{O1} = 54-7 = 47 ms
- Positive Phase Duration tO2 = 100-54 = 46 ms
- Blast Impulse (I): 15.297 Kpa-sec
- Maximum Reflected Blast Pressure on Right Wall = + 800 (526.85^0 C) @ 57ms

❖ **Left Wall:**

- Maximum Reflected Blast Pressure (P_r) on Left Wall = + 865.00 kPa @ 14ms
- Maximum Incident Blast Pressure (P_{so}) on Left Wall = + 600 Kpa @ 6ms
- Time of Arrival (t_A) = 6 ms
- Positive Phase Duration t_{O1} = 38-6 = 32 ms
- Positive Phase Duration tO2 = 100-32 = 62 ms
- Blast Impulse (I): 17.408 Kpa-sec
- Maximum Reflected Blast Pressure on Left Wall = + 900 K (626.85^0 C) @ 57ms

❖ Maximum -ve Reflected Blast Pressure Rear, Right & Left wall = - 89.283 kPa

- Increases Shock wave propagation due to Multiple Blast wave reflections from the time of Arrival till 100ms.

2. Blast Pressure Prediction Using Empirical Method:

The mass equivalent of trinitrotoluene (TNT) is used to simulate the impact of an explosion in which the energy released is equal to the mass of TNT, resulting in the same amount of damage. For the transformer tank rupture, the highest arc energy reported is used to calculate W_{TNT} for further blast analysis.

$$W_{TNT} = \frac{Explosion\ Energy}{H_{TNT}^{d}}\ x\ Efficiency\ factor$$

$$H_{TNT}^{d} = 4.1\ MJ/kg$$

The efficiency factor is 1.0 for the accurate prediction of transformer explosion energy. For uncertain data, it is recommended to apply a safety factor to the charge weights by approximately 20% i.e, 1.2. Thus, the formulae are reduced to:

$$W_{TNT} = \frac{E_{arc}}{4.1}\ x\ Efficiency\ factor$$

E_{arc} = (Ranganekar, R. 2024) for 500MVA TXF-1

Table 5: TNT Equivalent for EHV Transformer Explosion

Sr. No	Type of TXF	Arc Energy E_{arc} (MJ)	Explosion Energy (MJ)	Heat of Detonation (MJ)	Efficiency Factor	W_{TNT} (Kg)
1	500 MVA-1	32.1	32.1	4.1	1	7.8

To calculate peak overpressure and maximum reflected overpressure, a scaled distance & Angle of Incidence (α).

$Z = \frac{RG}{(W_{TNT})^{1/3}}$; $R_h = \sqrt{(R_G)^2 + (h)^2}$; $\alpha = \tan^{-1}\left(\frac{h}{R_G}\right)$

Where,

R_h = Standoff distance

R_G = Ground Standoff distance
h = Height above ground
Z = Scaled Distance [m]
W_{TNT} = Weight of the explosive [kg].

As the Transformer Tank is mounted on Top of the Plinth, the Blast pressure on the RC wall within the oil-water collection pit area is ignored. All Blast Pressure is considered to be transferred on the rectangular geometrical configuration RC wall above the top of the plinth, which will be 10.0m in height. As the Explosion is almost at the Ground surface, SURFACE BURST or Hemispherical Blast is considered. As the Transformer Steel Tank is surrounded by a Gavel supported on steel grating, reflection or amplification by the ground or gravel surface is ignored. Thus, the formation of MACH STEM is neglected.

Table 6: Scaled Distance for Rear RC Wall @ R_G=3.63 & Side RC Walls @ R_G=5.27m

Element Number	Ground Stand Off Distance (R_G) m	Above Plinth Level to Center of Element h (m)	Stand off Distance R_h = $((R_G)^2 + (h)^2)^{1/2}$	Angle of Incidence (α) Degrees	W_{TNT} (Kg)	Scaled Distance Z (m)
1	3.63	0.5	3.7	7.8	7.8	1.85
2	5.27	0.5	5.3	5.4	7.8	2.67

Blast Load prediction on the structure due to the explosion of the EHV Transformer will be evaluated using the following two Empirical methods.

I. Mills' Empirical Equation
II. Kingery & Bulmash Equations

Evaluation of blast load will be done for the positive phase duration & negative phase will be neglected. The Kingery-Bulmash curves (Positive Phase Duration) for Surface Burst will be evaluated. AT BLAST is a software program used, which is based on UFC 3-340-02, "Structures to Resist the Effects of Accidental Explosions," utilizing the Kingery-Bulmash equations and fitting.

Table 7: Blast Load Prediction using Mills Empirical Method for Rear Wall (RW)

Element Number	Ground Stand Off Distance (R_G) m	Above Plinth Level to Center of Element h (m)	Stand off Distance $R_h = ((R_G)^2 + (h)^2)^{1/2}$	Angle of Incidence (α) Degrees	W_{TNT} (Kg)	Scaled Distance Z (m)	Pso By Mills 1987 (Positive Phase Duration)				Reflected Pressure	
							$\frac{1772}{Z^3}$	$\frac{114}{Z^2}$	$\frac{108}{Z}$	Pso (Kpa)	$2P_{so}$	P_r (Kpa)
0	**3.63**	**0**	**3.63**	**0.0**	**7.8**	**1.83**	**288.4**	**34.0**	**59.0**	**313.4**	**626.7**	**628.6**
1	3.63	0.5	3.7	7.8	7.8	1.85	281.4	33.4	58.5	306.5	612.9	614.8
2	3.63	1.5	3.9	22.5	7.8	1.98	228.5	29.1	54.6	254.0	507.9	509.7
3	3.63	2.5	4.4	34.6	7.8	2.22	161.7	23.1	48.6	187.2	374.4	376.0
4	3.63	3.5	5.0	44.0	7.8	2.54	108.0	17.7	42.5	132.8	265.7	267.1
5	3.63	4.5	5.8	51.1	7.8	2.91	71.6	13.4	37.1	95.3	190.6	191.9
6	3.63	5.5	6.6	56.6	7.8	3.32	48.4	10.3	32.5	70.6	141.1	142.4
7	3.63	6.5	7.4	60.8	7.8	3.75	33.6	8.1	28.8	54.2	108.5	109.7
8	3.63	7.5	8.3	64.2	7.8	4.20	23.9	6.5	25.7	43.2	86.4	87.5
9	3.63	8.5	9.2	66.9	7.8	4.66	17.5	5.3	23.2	35.5	70.9	72.1
10	3.63	9.5	10.2	69.1	7.8	5.13	13.2	4.3	21.1	29.9	59.8	60.9
									Av. Pso =	**138.4**	**Av. Pr =**	**278.3**

Table 8: Blast Load Prediction using Mills Empirical Method for Side Wall (SW)

Pso By the Kingery-Bulmash curves (Positive Phase Duration) Surface Burst for Rear Wall (RW)

Element Number	Ground Stand Off Distance (R_G) m	Above Plinth Level to Center of Element h (m)	Stand-off Distance $R_h = ((R_G)^2 + (h)^2)^{1/2}$	Angle of Incidence (α) Degrees	W_{TNT} (Kg)	Scaled Distance Z (m)	$W^{1/3}$	P_{so} (Kpa)	P_r (Kpa)
0	**3.63**	**0**	3.63	0.0	**7.8**	1.83	**1.98**	**347.91**	**1381.36**
1	3.63	0.5	3.7	7.8	7.8	1.85	1.98	332.95	1272.01
2	3.63	1.5	3.9	22.5	7.8	1.98	1.98	294.96	1025.39
3	3.63	2.5	4.4	34.6	7.8	2.22	1.98	250.00	708.64
4	3.63	3.5	5.0	44.0	7.8	2.54	1.98	168.37	512.00
5	3.63	4.5	5.8	51.1	7.8	2.91	1.98	122.04	297.65
6	3.63	5.5	6.6	56.6	7.8	3.32	1.98	93.29	280.00
7	3.63	6.5	7.4	60.8	7.8	3.75	1.98	74.26	145.13
8	3.63	7.5	8.3	64.2	7.8	4.20	1.98	59.57	174.80
9	3.63	8.5	9.2	66.9	7.8	4.66	1.98	49.30	94.39
10	3.63	9.5	10.2	69.1	7.8	5.13	1.98	41.09	77.22
						Average =		**166.7**	**542.6**

Table 9: Blast Load Prediction using Kingery-Bulmash Empirical Method for Side Wall (SW)

P_{so} By the Kingery-Bulmash curves (Positive Phase Duration) Surface Burst for Side Wall (SW)

Element Number	Ground Stand Off Distance (RG) m	Above Plinth Level to Center of Element h (m)	Stand-off Distance $R_h = ((R_G)^2 + (h)^2)^{1/2}$	Angle of Incidence (α) Degrees	W_{TNT} (Kg)	Scaled Distance Z (m)	$W^{1/3}$	P_{so}	P_r
0	**5.27**	**0**	5.27	0.00	7.8	2.66	1.98	**150.03**	**460.64**
1	5.27	0.5	5.29	5.42	7.8	2.67	1.98	148.17	453.26
2	5.27	1.5	5.47	15.90	7.8	2.76	1.98	138.38	407.20
3	5.27	2.5	5.83	25.40	7.8	2.94	1.98	120.73	333.57
4	5.27	3.5	6.32	33.61	7.8	3.19	1.98	101.97	274.20
5	5.27	4.5	6.93	40.52	7.8	3.49	1.98	84.53	226.29
6	5.27	5.5	7.61	46.25	7.8	3.84	1.98	70.46	226.22
7	5.27	6.5	8.36	50.99	7.8	4.22	1.98	58.81	166.37
8	5.27	7.5	9.16	54.93	7.8	4.62	1.98	49.71	136.52
9	5.27	8.5	10.00	58.23	7.8	5.04	1.98	42.54	110.87
10	5.27	9.5	10.86	61.00	7.8	5.47	1.98	36.96	91.98
						Average =		**91.12**	**262.5**

Table 10: Blast Parameters (Positive Phase) For Surface Bursts on Rear Wall (RW)

Element Number	P_{so}	P_r	Shock Wave Speed U (m/ms)	$\frac{L_W}{W^{1/3}}$	Incident Impulse I_s (kPa-ms)	Arrival Time t_A (ms)	Positive Phase Duration t_O (ms)	Wave-length L_w (m)	Reflected Impulse I_r (kPa-ms)	t_d at 90^0 (Fully Incident)	t_d at $\alpha=0^0$ (Fully Reflected)
0	**347.91**	**1381.36**	**0.67**	**0.5**	**290.27**	**2.85**	4.2	1.0	**804.62**	**1.67**	**1.16**
1	332.95	1272.01	0.66	0.5	297.65	2.95	4.0	1.0	779.25	1.71	1.23
2	294.96	1025.39	0.63	0.5	270.96	3.26	4.0	1.0	687.48	1.84	1.34
3	250.00	708.64	0.58	0.6	248.04	4.08	4.2	1.2	544.13	2.16	1.54
4	168.37	512.00	0.53	0.6	214.91	5.15	5.0	1.2	429.54	2.55	1.68
5	122.04	297.65	0.48	0.8	188.09	6.72	6.0	1.6	338.6	3.08	2.28
6	93.29	280.00	0.46	0.8	167.96	8.42	6.0	1.6	278.13	3.6	2.8
7	74.26	145.13	0.44	0.9	151.96	10.22	6.9	1.8	236.15	4.09	3.25
8	59.57	174.80	0.42	1	137.48	12.35	7.4	2.0	202.77	4.62	3.53
9	49.30	94.39	0.41	1	125.62	14.55	7.9	2.0	177.88	5.09	3.77
10	41.09	77.22	0.40	1.3	114.59	17.07	7.9	2.6	156.99	5.57	4.07
	166.7	**542.6**				**7.97**	**5.8**				**2.42**

Table 11: Blast Parameters (Positive Phase) For Surface Bursts on Side Wall (SW)

Element Number	P_{so}	P_r	Shock Wave Speed U (m/ms)	$\frac{L_W}{W^{1/3}}$	Incident Impulse I_s (kPa-ms)	Arrival Time t_A (ms)	Positive Phase Duration t_O (ms)	Wave-length L_w (m)	Reflected Impulse I_r (kPa-ms)	t_d at 90^0 (Fully Incident)	t_d at $\alpha=0^0$ (Fully Reflected)
0	**150.03**	**460.64**	**0.51**	**0.7**	**204.91**	**5.66**	**5.75**	1.39	**512.83**	**2.73**	**2.23**
1	148.17	453.26	0.510	0.7	204.22	5.72	5.66	1.39	508.70	2.75	2.40
2	138.38	407.20	0.500	0.7	198.16	6.06	5.46	1.39	476.42	2.88	2.34
3	120.73	333.57	0.480	0.8	187.26	6.78	5.95	1.59	422.51	3.08	2.53
4	101.97	274.20	0.470	0.9	174.44	7.81	5.95	1.79	365.35	3.42	2.66
5	84.53	226.29	0.450	0.9	160.92	9.15	5.95	1.79	312.28	3.81	2.76
6	70.46	226.22	0.430	0.95	148.51	10.71	6.95	1.89	269.20	4.22	2.38
7	58.81	166.37	0.420	1	136.65	12.49	7.44	1.98	233.75	4.65	2.81
8	49.71	136.52	0.410	1	126.11	14.45	7.74	1.98	204.78	5.07	3.00
9	42.54	110.87	0.400	1.25	116.66	16.56	7.94	2.48	181.75	5.48	3.28
10	36.96	91.98	0.390	1.1	108.32	18.77	8.14	2.18	162.85	5.86	3.54
	91.12	**262.5**				**10.4**	**6.6**				**2.72**

Table 12: Comparison of CFD Results with Empirical Method for Rectangular Geometrical configuration

Blast Wave Parameters	**CFD Result**	**Empirical Method Kingery-Bulmash**
Max Reflected Pressure (Pr)-RW	910 Kpa	1381.36 Kpa
Max Reflected Pressure (Pr)-SW	810 Kpa Right Wall 865 Kpa Left Wall	460.64 Kpa
Max Incident Pressure (Pso)-RW	NIL	347.91 Kpa
Max Incident Pressure (Pso)-SW	410 Kpa Right Wall 600 Kpa Left Wall	150.03 Kpa
Average Reflected Pressure (Pr)-RW	545 Kpa	542.6 Kpa
Average Reflected Pressure (Pr)-SW	200 Kpa Right Wall 210 Kpa Left Wall	262.5 Kpa
Arrival Time (t_A)	6 to 7 ms	7.97 to 10.4 ms
Rear Wall Positive Phase Duration (t_O)	• t_{O1} = 32 ms • t_{O2} = 62 ms	5.8 ms
Side Wall Positive Phase Duration (t_O)	• t_{O1} = 47 ms Right Wall • t_{O2} = 46 ms Right Wall • t_{O1} = 32 ms Left Wall • t_{O2} = 62 ms Left Wall	6.6 ms
Maximum -ve Reflected Blast Pressure Rear, Right & Left wall	**- 89.283 kPa**	NIL
Blast Impulse (I), Kpa-Sec	• Rear Wall=17.970 • Right Side Wall=15.297 • Left Side Wall=17.408	• Rear Wall=2.281 • Side Wall=0.870
Temperature	• Maximum Temperature Rear Wall subjected = + 900 K (626.850 C) • Maximum Reflected Blast Pressure on Right Wall = + 800 K (526.850 C) • Maximum Reflected Blast Pressure on Left Wall = + 900 K (626.850 C)	NIL
Blast Wave Velocity	• Maximum Blast Wave Velocity = 653.05 m/sec • Minimum Blast Wave Velocity = 283.33 m/sec	• Maximum Blast Wave Velocity = 510.0 m/sec • Minimum Blast Wave Velocity = 390.0 m/sec
Total Positive Phase Duration	100ms	14 to 17ms

CFD analysis can capture Shock wave propagation due to Multiple Blast wave reflections from the time of Arrival till 100ms, whereas the Empirical Method lacks. The CFD pressure-time history captured a positive phase duration of 100ms, whereas the empirical method yields a positive phase duration of 14 to 17ms. Table no. 7 to 11 gives the empirical method results at different conditions.

Conclusion

This research successfully demonstrates the application of Computational Fluid Dynamics (CFD) as an effective and accurate tool for computing blast loads on structures resulting from EHV transformer explosions. CFD results for rectangular configuration TXF compound give Maximum Reflected Blast Pressure (Pr) on Rear Wall = + 910.00 kPa @ 8ms, Right Wall (RSW) = + 805.00 kPa @ 14ms, Left Wall (LSW) = + 865.00 kPa @ 14ms, and Maximum -ve Transformer Blast Pressure on all walls as -89.256 kPa @ 50ms. In both cases, Blast Waves Arrival Time (t_A) remains between the range of 6 to 10.4ms. Enables Capture of amplified Shock wave propagation due to Multiple Blast wave reflections from the time of Arrival till 100ms, which is not possible with Empirical Methods. Obstacles (radiators, tanks) significantly alter wave propagation.
Comparison of CFD Results with the Empirical Method indicates that RW is subjected to a single wave P_r of 51.75% higher than CFD, but for a very short time, RSW is subjected to a Peak P_r of 75.84% higher than the Empirical Method, and LSW is subjected to a Peak P_r of 87.78% higher than the Empirical Method. The CFD pressure-time history captured a positive phase duration of 100ms, whereas the empirical method yields a positive phase duration of 14 to 17ms only. CFD also generates a Temperature-Time-History for the surrounding RC Walls of the Rectangular Configuration TXF Compound, ranging from 526.85^0 C to 626.85^0 C.
The Extreme loads caused by explosions should be considered in the design and analysis of structures subjected to an explosion of an HV Power Transformer. The findings contribute valuable knowledge toward designing safer substation environments, enhancing the resilience of critical infrastructure, and informing engineering standards for blast protection in the power sector. Structural Safety is provided by introducing RC Blast-Resistant walls around the Transformer to absorb or deflect blast energy, thereby protecting surrounding structures. Construct a transformer housing with reinforced walls using materials such as reinforced concrete or steel to contain or mitigate the effects of blasts. Experimental studies cannot generally be preferred due to several difficulties. In place of this, numerical and analytical studies like CFD are preferred. In conclusion, CFD-based analysis proves to be a vital approach in accurately estimating blast loads and developing robust engineering solutions for explosion risk management in EHV transformer installations.
This research will provide a scientific basis for understanding the impact of transformer explosions on structures using CFD simulations. Pressure-Time History derived from CFD Analysis can be used to study the Structural Dynamic Response using Time-History or Transient Structural Analysis. The findings will help design safer & economical Transformer Compound structures by studying the structure's dynamic response using dynamic analysis software such as ANSYS Workbench, applying Pressure-Time History loading and Thermal Analysis using Temperature-Time History.

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