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Research article

MODELING THE EFFECTS OF MOSQUE EXPLOSION ON PRAYERS

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Keywords: Blast injuries, blast-structure interaction, CFD, compressible flow, injury criteria, injury prediction, numerical analysis

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Abstract

Mosques are temples for Muslims in which five prayers are held a day. The continuous escalation of terrorist threats in general and on mosques, in particular, necessitates the importance of protecting people and infrastructure from the burdens of malicious deliberate bombings. The consequences of the blast overburdens are catastrophic, including injuries, deaths, material and economic losses, and social upheaval. The current research employed numerical simulation to investigate the influence of an intentionally induced explosion in a confined, densely populated space on expected human casualties. The case study is a typical mosque building with an area of 600 square meters. Its maximum capacity is 720 prayers (Muslim worshipers), distributed in 12 rows, one behind the other. A detonation occurred as a result of a 1.15 kg TNT bomb exploding in the first row behind the Imam (leader of prayers). The time history of overpressure and speed was monitored at six different points. The four types of blast injuries, primary, tertiary, secondary, and quaternary, have been evaluated. The primary targets, the imam and prayers near the center of the explosion, are more likely to die from the tertiary blast injury. Prayers close to reflective walls, especially near the corners of the mosque, are at risk of death due to the primary blast injury. High winds have been found to cause more severe tertiary injuries than primary injuries resulting from blast overpressure. The information presented in this paper is useful for assessing post-blast damage and for estimating potential blast hazards from explosions. Appropriate design and provision of emergency exits can reduce the rates of physical injury and death resulting from explosions.

Abbreviation & Nomenclature

A, B, C Probes located along the centerline of the mosque
D, E, F Probes located along the sidewall of the mosque
e Total energy
F Inviscid flux
i Internal energy
p Pressure
T Time
U Conservative variables
u Velocity in *x* direction
v Velocity in *y* direction
γ Specific heat ratio
ρ Density
ξ Curvilinear coordinate
ζ Curvilinear coordinate

1. INTRODUCTION

Recently, terrorist attacks are increasingly taking place in densely populated buildings due to the changing nature of intellectual conflict. This dangerous act threatens human lives, security, property, and buildings.[1] For instance, on January 30, 2023, an undetected perpetrator managed to infiltrate a mosque in Peshawar, Pakistan. He detonated a suicide vest while standing in the first row of prayers (Muslim worshipers) causing a powerful explosion that collapsed the roof of the mosque, killed 84 people, and twice as many were injured.[2] Knowing that this incident was preceded by an explosion in another mosque in Peshawar in March 2022, which killed at least 61 people and injured 196 others.[3] These bombings have often been repeated as a result of terrorist attacks in mosques in many cities around the world. To mention, but not to be limited, about six bombings targeted mosques between 2015 and 2016 in several cities in the Kingdom of Saudi Arabia, killing dozens and injuring hundreds.[4]

Detonation of high-level explosives such as trinitrotoluene (TNT) produces a supersonic blast wave. A lot of energy is released quickly resulting in an environment of

high temperature, high overpressure, and high wind speed. The overpressure is attributed to the incident blast wave due to the detonation. An idealized blast wave is characterized by an immediate increase in pressure to the peak overpressure, which subsequently decreases over time, followed by a period of underpressure.[5] The portion of the wave that exceeds ambient pressure is known as the positive phase, with its duration being termed the positive phase duration. The duration of the overpressure positive phase increases with the energy released and distance from the center of the explosion.[5] As the standoff distance increases, the duration of the positive pulse increases, but with a reduced amplitude. The blast parameters at a specific location can be estimated from the pressure-time history recording. When the blast wave interacts with solid structures, it produces a reflected wave which complicates the flow field. Blast wave reflections from rigid structures can magnify the overpressures many times over.[6-8] A mosque building as a confined space can greatly complicate the development of a blast wave. The interaction between the aforementioned mechanisms is complex, and several past studies have tried to shed light on the problem.[6-9] Analysis has demonstrated that confinement of explosions results in more serious injuries.[10-12]

Conducting scientific experiments on shock waves to investigate their impact on buildings is immensely difficult.[8] Unfortunately, practical experiments to identify the effect of blast waves on humans are impossible. This makes it challenging to understand the mechanisms caused by blast waves, including human injuries. However, simulations can help us gain a better understanding of these mechanisms, which in turn, helps us develop strategies to prevent or mitigate the effects of blast exposure This research employs computational fluid dynamics (CFD) to assess the potential harm caused by blast injuries and minimize their impact. The CFD has emerged as a useful tool for evaluating the risk of blast injuries and minimizing their effects. This approach involves simulating the complex behavior of fluids and gases in response to explosive events. By analyzing these simulations, one can gain a better understanding of the physics underlying confined explosions in mosques, which are known to be particularly hazardous. Moreover, one can make accurate predictions about the pressure and blast waves generated by explosive events, as well as their effects on the human body. This information can help us better understand the potential for primary blast injury in different locations and develop strategies to mitigate the risk of such injuries. Therefore, the results of this study are significant because they provide valuable insights into the mechanisms that govern blast wave propagation and their impact on human bodies. This knowledge can help develop more effective safety measures that can protect people from blast injuries.

The following five main sections offer an in-depth analysis and detailed insights into the research process. The second section explores the different types of blast injuries, offering a detailed examination of their characteristics and causes. The third section delves into the definition of the test case, discussing its scope, objectives, and methodology. The fourth section is dedicated to the research methodology, providing a detailed description of the tools, techniques, and procedures used to conduct the study. The fifth section presents and analyzes the simulation results, offering a critical evaluation of the findings and their implications for the research question. Finally, the last section draws conclusions based on the insights gained from the study.

2. BLAST INJURIES

Exposure to a high-speed explosive bomb can cause injuries ranging from minor to serious or even fatal.[13] It affects different human body systems often leading to long-term complications. The severity of injuries depends on the type and size of explosives used, the distance of the casualty from the center of the explosion, the direction and angle of the blast wave, the duration of the positive blast phase, and the surrounding space whether indoors or outdoors.[13] Moreover, other factors such as the political and economic conditions of the country where the accident occurred can also influence the severity of injuries and risks. Immediate death can occur from a severe head injury, major internal injury, amputation, or impalement to the body. However, blast injuries can be grouped into four categories in the medical community primary, tertiary, secondary, and quaternary, based on the impact on the human body.[13,14] Each of them will be explained in the following paragraphs.

Primary blast injuries (PBIs) occur upon exposure to the overpressure of a blast wave. It can affect the air-filled organs, such as the auditory (ear), pulmonary (lung), and brain systems, without outward signs of injury.[13,14] The sudden change in pressure caused by detonation may rupture the eardrum and damage the middle ear. However, even a low overpressure of 35kPa can cause tympanic membrane perforation and hearing loss.[15,16] The sudden change in atmospheric pressure caused by blast waves can greatly disrupt the normal function of the airways and alveoli in the lungs. This can cause instant death from a lung injury in which bleeding leads to suffocation.[17] At the very least, the overpressure can lead to various symptoms, including difficulty breathing, chest pain, coughing, and respiratory distress.[17,18] The human brain is susceptible to blast injuries, and even relatively low levels of overpressure can cause significant damage resulting in cognitive and behavioral impairments.[19] Even a personal mine or hand grenade with an explosive mass as small as 100 grams can pose a risk of death due to lung injury.[20] Moreover, the primary effects of the explosion could also affect the abdominal cavity, which could result in organ damage or at least minor effects, such as stomach pain, vomiting, and diarrhea.[21] PBIs can be predicted using the thresholds of published multiple injury criteria that develop in free-air explosions.[10] Although it is difficult to determine specific values for burst overpressure in humans, the prediction of PBIs can be considered as a general guideline because it is based on ideal overpressure.[8] The actual effects of an explosion on an individual can vary greatly depending on the influencing factors mentioned previously that need to be taken into ac-

count. For an unprotected person, serious injury may lead to death as a result of blast peak overpressure at the level of 689kPa, and death is inevitable if the overpressure reaches 1,379kPa.[10]

Tertiary blast injuries (TBIs) that are caused by high winds of secondary blast waves. It is a high speed of hot air flow moving immediately after the blast wave. The published evidence indicates that human health can be severely affected by the dynamic pressure of wind.[22] The aerodynamic force of the wind behind the blast wave causes the human balance to become unstable and throws it strongly with such force that it hits hard or sharp surfaces.[11,23] This can lead to deaths and serious human injuries such as fractures, traumatic amputations, bruises, and cuts.[24] Wind speed of less than 65km/h can lead to loss of balance, difficulty walking, and even difficulty performing simple physical tasks.[22] Winds of up to 72km/h can cause falls to elderly people and cyclists.[24] Winds of speed 90-120km/h can lead to loss of human life[23] and material damage to infrastructure.[25] The Fujita Hurricane Scale (FHS) divides wind intensity into six levels based on their speed.[25] The lowest speed level that has an impact is described as gale wind (65-115 km/h), which could uproot a small tree. The last wind level in the FHS ranking is called incredible wind (> 420 km/h), which can throw a car over a distance of 90m. However, the effect of the drag aerodynamics force of the wind depends on the orientation of the human body against the wind. The lateral position body can experience a drag force of 58% of the frontal position for a wind speed of 144km/h.[23]

Secondary blast injuries (SBIs) are associated with glass breakage[26] and the impact of flying debris and bomb fragments on the human body.[27] Moreover, the explosive bomb is often filled with small iron balls, nails, or other objects that can be used as shrapnel to increase casualties.[28] Finally, quadrant blast injuries (QBIs) are blast-related injuries or illnesses that are not caused by primary, tertiary, or secondary injuries. QBIs can include burns, crush injuries, and breathing problems from dust, smoke, and toxic fumes. Furthermore, angina, hyperglycemia, and hypertension can be considered as QBIs. In addition, exacerbation of injuries and chronic diseases can occur due to failure to obtain timely medical care.

3. PROBLEM DEFINITION

The layout of the considered test problem is shown in Fig. 1. The building represents a typical mosque building with an area of 600m^2 surrounded by high walls on all sides. The part that comes out from the front represents the place designated for the Imam (a prayer leader of a mosque). The entrance gate is located in the middle of the backwall. The mosque can accommodate up to 720 prayers distributed in 12 rows, with about 60 prayers standing in each row.

The simulation can be done for only half of the domain because the building is symmetrical in shape around the central line that runs from front to back. Therefore, the left boundary condition acts as a symmetry (centerline). This implies that the solution at the right boundary will be a mirror image of the left boundary's solution. This simplifies the problem or simulation to a great extent, and it reduces the total computational cost and becomes easier to calculate the solution. As for the other boundaries, they are treated as wall conditions, which means that the flow of the fluid or any other physical quantity will not pass through these boundaries. Inside the mosque, there are four columns with a diameter of 60cm that are an integral part of the physical construction of the mosque and provide necessary support to the building. However, in the model, these columns were not considered as their impact on the overall design was deemed to be insignificant.

Most reports of the previous events indicate that the explosion devices were caused by a suicide belt which is worn by a suicide bomber packed with explosive materials. It can be assumed that the explosion occurred as a result of the detonation of an explosive charge of 1.15kg from a TNT bomb. This weight is a typical light bomb that a person can carry maliciously.[11] The density of TNT is 1640kg/m^3, which is 4.8 times lighter than iron. Each kilogram (e.g. 610cm^3) of TNT releases 4184kJ of energy, which can obliterate a small vehicle.[29] The produced blast wave parameters at a 0.5m stand-off distance are estimated using empirical formulas (Stewart[30]; Kingery and Bulmash.[5] The high-speed explosives produce blast waves that escalate into shock waves.[29] According to the blast parameters produced by this weight and stand-off distance, it roughly corresponds to a shock wave of Mach number 6.62. For other explosive materials, one can estimate the mass of TNT equivalence.[29] Overpressure and speed histories in several positions were monitored to illustrate the effects on the prayers. There are six probe points (A, B, C, D, E, and F) near the wall and in the middle of the mosque as shown in Fig. 1.

It is expected that the location of the explosion will lead to a change in the resulting damage to the human and the building. Most of the previous explosions in mosques occurred behind the imam in the first row and the middle of the mosque.[4] However, a few incidents took place near the entrance gate close to the last row of prayers in an unplanned manner as a result of the security pressures faced by the assailant carrying the explosive device.[4] For instance, a bomb was thrown into a church hall next to the entrance in Egypt.[31] However, it is expected that the effect of an explosion inside the mosque near the entrance will be almost similar to the effect of an explosion in the first row of the mosque. The detonation is initiated directly behind the Imam in the first row of the prayers, which is indicated by a large semicircle in Fig. 1. The ambient atmospheric conditions of density, pressure, and temperature of 1.225kg/m^3,101325Pa, and 20^oC, respectively, are taken as reference.

4. COMPUTATIONAL METHODOLOGY

Computational fluid dynamics has been successfully used to investigate fluid flows to shed light on the complicated fluid dynamics understanding of transient blast waves. Such numerical simulations are too difficult to investigate with expensive shock tube experiments. The present study

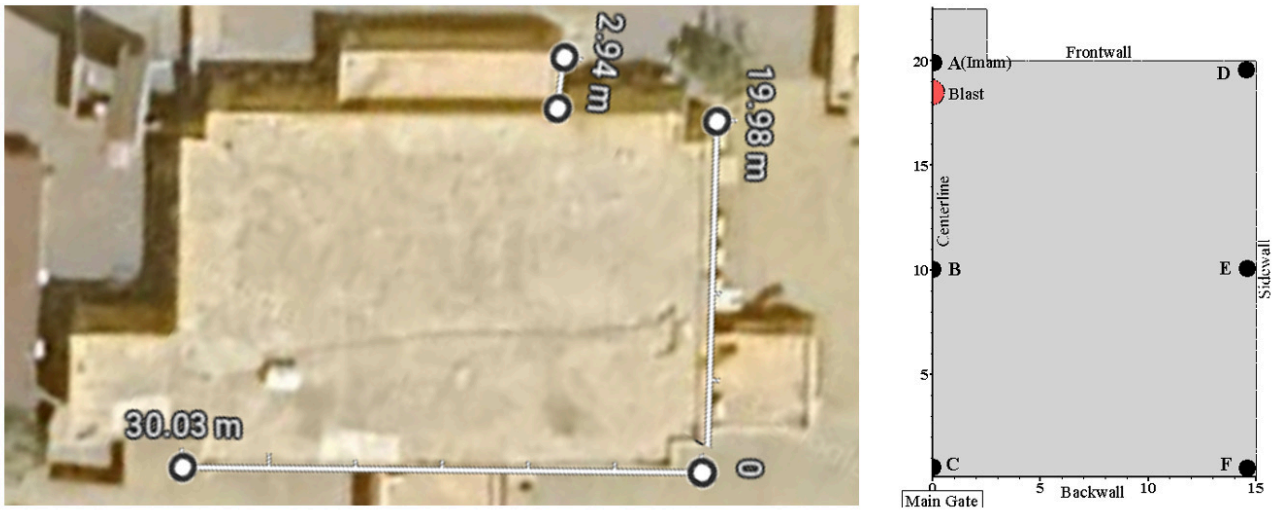

Fig 1. Layout of the mosque (left) and simulation domain showing the assigned probe locations (right).

models explosion and consequent blast wave propagation in air. The inviscid Euler equations are numerically solved by a finite volume method using Ansys Fluent. The justification for the common use of Euler equations to model shock waves is that the compressible flow is mostly subject to convective effects.[6] This is due to the fact that the viscous effects are concentrated only in the boundary layer adjacent to the solid surfaces.[6]

The Euler equations can be written in matrix form and the two curvilinear co-ordinates, ξ and ζ, as:

$$\frac{\partial U}{\partial t} + \frac{\partial F_\xi}{\partial \xi} + \frac{\partial F_\zeta}{\partial \zeta} = 0 \tag{1}$$

where F represents the inviscid flux, t is time, and U is the conservative variables:

$$U = (\rho, \rho u, \rho v, e)^T \tag{2}$$

where ρ is the density, u and v are the velocity components, and e is the total energy per unit volume. The pressure, p, is calculated by the ideal gas equation of state based on internal energy, i:

$$p = \rho(\gamma - 1)i \tag{3}$$

The explosion flow is simulated as an ideal gas, which has a specific heat ratio, γ, of 1.4 and a gas constant of 287$J/kg.K$.

A second-order least-square cell-based scheme has been selected for the compressible flow spatial discretization (Liou, 1996). Transient terms are estimated by the first-order explicit scheme which is less expensive and more accurate than implicit. The Courant–Friedrichs–Lewy number (CFL) is set to a low number of 0.5 which leads to a small time step to keep the numerical simulation stable and to minimize non-physical oscillations.

The computational domain is discretized using a structured quadrilateral mesh of cell size of 4×10^{-2} m^2 which reveals 45600 cells. Grid independency numerical experiments demonstrate that the initial mesh size used in combination with dynamic mesh adaptation proves suitable for capturing qualitative and quantitative flow features. In regions where the density gradients exceed 5% of the local normalized value, the grid is adaptively refined up to three times. Refining one cell at a time creates four new cells, so refining three times results in a cell size of 6.25×10^{-4} m.[4] In contrast, when the density gradient is below a 2% threshold meaning that important flow features have passed away, the mesh becomes coarse. The adaptive mesh procedure can result in a mesh size of more than one million cells. However, the accuracy of the results is limited by the available computer facilities (Intel Core i7 with 12.0 GB RAM), and for this reason, a limit was placed on the size of the mesh, which is half a million cells.

5. RESULTS AND DISCUSSION

5.1. EXPLOSION VISUALIZATION

The present paper discusses the simulation of the detonation of a 1.15kg TNT bomb. These explosive weights represent a typical value of an explosive that can be maliciously carried in the first row behind the Imam. In this section, several numerical visualization images of the explosion are presented, which predict all the salient features of blast wave interaction and reflections. Schlieren, based on the density gradient magnitude, is shown in Fig. 2. It illustrates the evolution of the explosion propagation and decay at different time instants. The corresponding surface overpressure and velocity magnitude (speed) contours are shown in Figs. 3 and 4, respectively.

The incident blast wave arrives at the Imam's position (probe A) after 2ms from the detonation onset, Fig. 2. A bubble of light liquid and vacuum forms at the center of the explosion, Fig. 3. At the time 14ms, the second frame shows the movement of the blast front to probe B. The blast wave covers the entire cavity in the front of the mosque, showing many shock-structure and shock-shock interactions and reflections. As shown in schlieren, Fig. 2, the center of the explosion appears to be experiencing what is called the Richtmyer–Meshkov instability due to the impulsive acceleration of different-density gases.[6,7] As time progresses, the third frame at 20 20ms exhibits the blast wave reaching the front

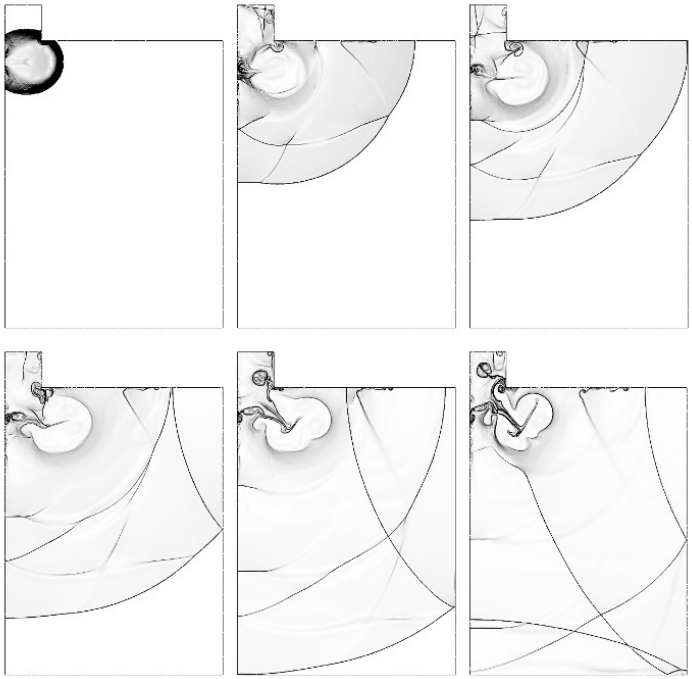

Fig. 2. Sequence of schlieren images as the blast incident wave reaches the assigned probe locations, A (2*ms*), B (14*ms*), D (20*ms*), E (28*ms*), C (38*ms*), and F (48*ms*).

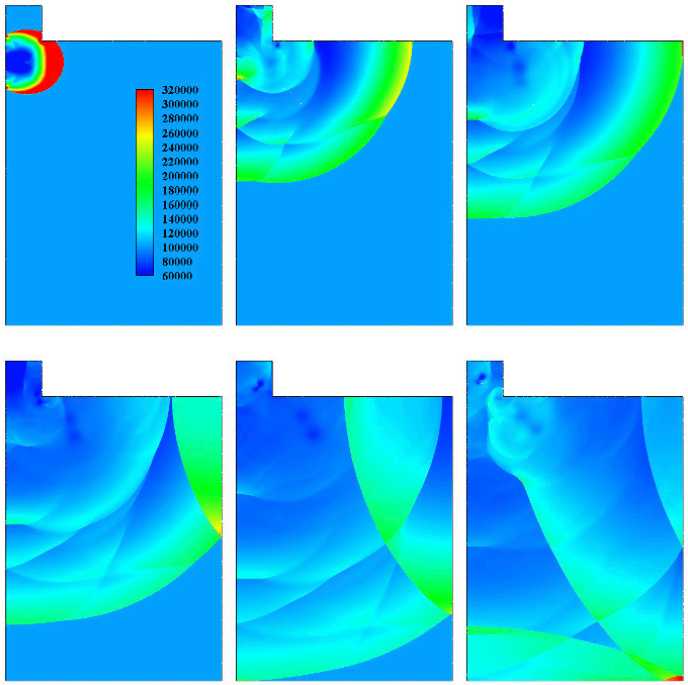

Fig. 3. Sequence of pressure contours (in Pascal) as the blast incident wave reaches the assigned probe locations, A (2*ms*), B (14*ms*), D (20*ms*), E (28*ms*), C (38*ms*), and F (48*ms*).

corner (point D). It is observing the development of secondary waves emanating from the core of the explosion with high wind speed, see Fig. 4. They are moving behind the incident blast wave. The surface pressure images shown in Fig. 3 illustrate the attenuation of the blast. The decay can be attributed to the non-uniform flow behind the blast wave.

The fourth frame depicts that the blast after it collided with the sidewall for the first time. This shock-focusing event is called regular reflection, which happens because of the interaction between the incident and reflected shocks.[6, 32] The creation of high-pressure zones is a result of this interaction, and it can have significant implications for the surrounding environment.[6] Therefore, it's essential to un-

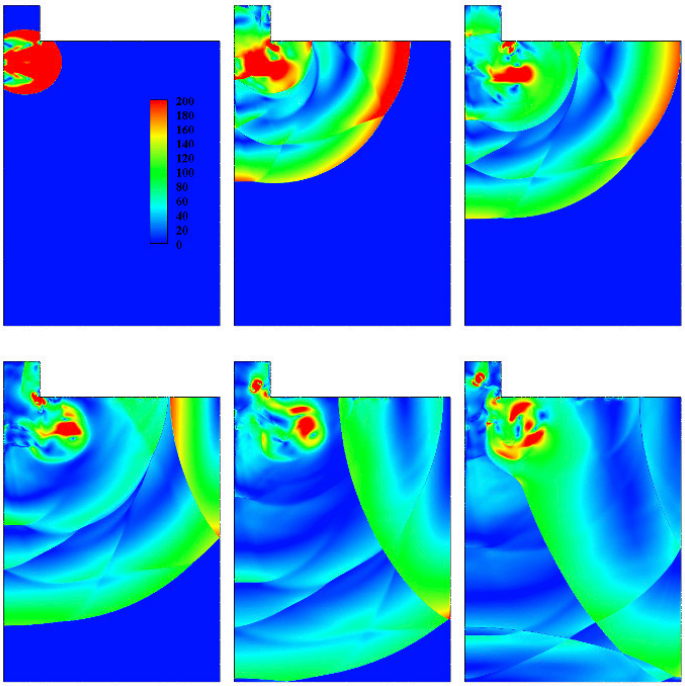

Fig. 4. Sequence of velocity magnitude (in m/s) as the blast incident wave reaches the assigned probe locations, A (2*ms*), B (14*ms*), D (20*ms*), E (28*ms*), C (38*ms*), and F (48*ms*).

derstand the mechanics of shock-focusing events to predict the impact of confined explosions and mitigate any potential risks. As a result of consistent reflection, the point of interaction formed on the sidewall gradually moves towards the back corner while still maintaining the adhesion of the incident blast wave and the reflected shock.[6] At t=28*ms* (as seen in Fig. 3), the interaction point of the high-pressure zone on the sidewall shifts towards the middle of the wall, at point E. By t=38*ms*, the incident blast wave reaches the entrance gate at probe C, while the reflected shock from the sidewall moves towards the center of the mosque. Additionally, a secondary shock, which follows the incident wave, approaches the sidewall. The back corner of the mosque, the location of probe F, is exposed to the interaction of three shock waves, the incident blast wave, and two reflected shocks from the sidewall and backwall, see last frame of Fig. 2. For this reason, as shown in the last frame of pressure contours of Fig. 3, the back corners of the mosque are areas of high concentration of overpressure.

It takes about 48*ms* from the beginning of the explosion until it hits the entire space of the mosque. The complex blast wave pattern emerges due to blast reflection and shock-shock interaction. Therefore, the center of the explosion has experienced several shock wave interactions and its shape has been constantly modified, Fig. 2. Comparing the overpressure and velocity contours, shown in Figs. 3 and 4, respectively, illustrate that they are not harmonious spatially and temporally. In other words, the speed of the wave at a given location and time does not necessarily have to be accompanied by high pressure. As time evolves, the velocity magnitude shown in Fig. 4 indicates that the speed of the blast wave gradually decreases.

Figure 5 shows the time history of the blast overpressure in the considered location of the pressure probes, A-F. The times when the incident blast wave reaches each probe are marked by the sudden surge in overpressure. The recurring peaks appearing in the pressure sensors are the result of the multiple pressure waves. The first peak overpressure at any probe is attributed to the incident blast wave. The highest peak overpressure is observed where the Imam stands in the front of the mosque, probe A, with a value of 334kPa and 2.4ms positive phase duration. The successive overpressure peak is due to the secondary waves moving after the incident blast wave. The peak overpressures gradually weaken as the blast wave propagates (Fig. 5). Then, the Imam location shows fluctuation in overpressure as a result of the multiple reflections and interactions of shock with each other, Fig. 5. The complex flow pattern resulting from the confined mosque explosion indicates that the Imam was exposed to several blast waves in addition to the incident wave. The peak overpressure is gradually weakened from 334kPa to about 105kPa as the blast wave propagates through probes B and C (Fig. 5). Although location C at the back of the mosque near the main entrance is relatively far from the center of the explosion, it records an overpressure higher than the middle of the mosque, probe B. On the other hand, at the locations near the backwall of the mosque, probes C and F, subsequent overpressure peaks take place at 48ms and 57ms (Fig. 5), respectively, before the positive phase of the previous shock resulting from the main shock ends. This in turn leads to a prolonged positive phase duration, increasing the likelihood of primary blast injuries, even at low overpressure values.[17]

Since the mosque is a confined space, due to wall reflections one can notice high peak overpressure of 312, 191,

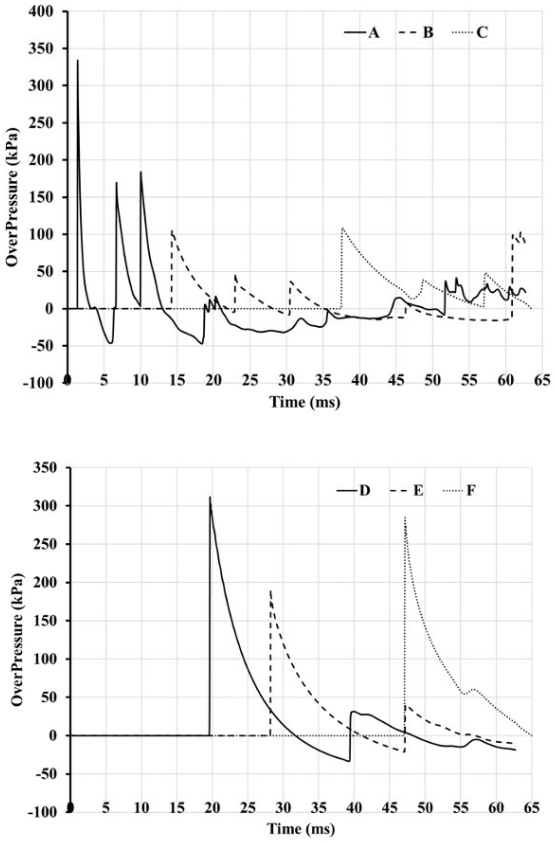

Fig. 5. Overpressure history at the assigned probe locations. Top: A, B, and C; Bottom: D, E, and F.

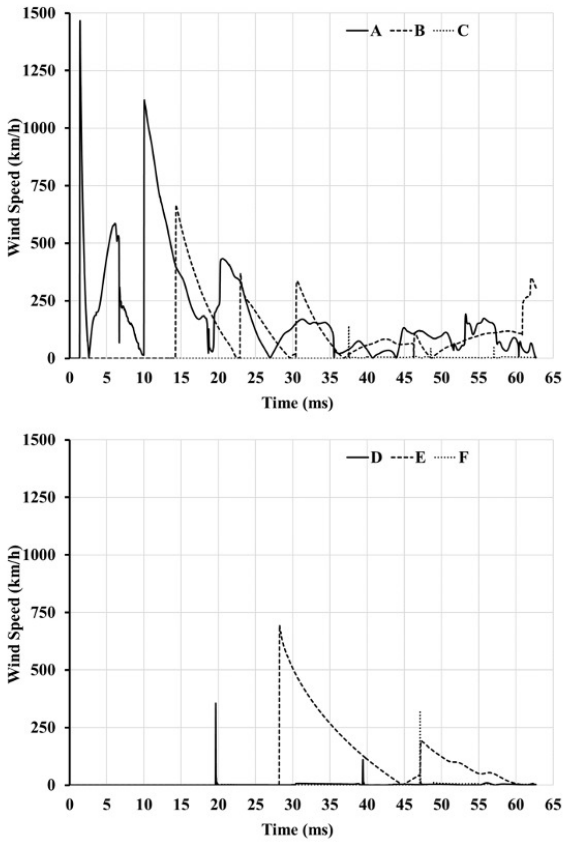

Fig. 6. Wind speed history at the assigned probe locations. Top: A, B, and C; Bottom: D, E, and F.

and 285kPa at probes near sidewall probes, D, E, and F, respectively. The mosque corners (i.e. D and F) are subject to high peak overpressure. Their peak overpressures reach a value close to probe A near the center of the explosion as shown in Fig. 5. It is noted that the peak overpressures at locations E and F are higher than the corresponding locations on the center of the mosque (i.e. B and C). Moreover, the proximal sidewalls show a higher duration of the positive phase of the overpressure. On the other hand, the history of maximum overpressure indicates that site B, located in the middle of the mosque, is the safest zone.

On the other hand, the time history of the blast wind in the considered six locations is shown in Fig. 5. Looking at the trends of the overpressure and speed curves, Figs. 5 and 6, respectively, are often identical. This is evident because the blast wind moves immediately after the overpressure wave. The highest maximum values of explosive wind speed are at A (1467km/s), then E, B, D, F, and finally C (141km/h), which is the lowest speed. It is noted that high wind speed can occur even at low overpressure. For instance, for probe A, the overpressure at time 21ms is 15kPa (Fig. 5) while the wind speed at the same location is 429km/h (Fig. 6). Moreover, it is also observed from Fig. 5 that the peak overpressure at location D (312kPa) is higher than location E (191kPa). However, the wind speeds at the two corresponding locations are 99 and 193km/h, respectively, which are the opposite of the corresponding overpressures, see Fig. 6.

5.2. PRIMARY BLAST INJURIES (PBIS)

Figure 7 shows the combination of PBI criteria (represented by solid and dashed lines) that defines the zones of relevant blast loading conditions based on the predictions made by Denny *et al.*[10] It can be summarized that eardrum ruptures[15,16] and 50% mild brain haemorrhage[33] that can be tolerated by prayer are independent of the blast positive-phase duration. In contrast, lung injuries[17,20] depend on the pressure overload and positive phase duration. However, for higher blast duration, lung injury mortality becomes less duration-dependent. The PBI threshold (onset) relates to the minimum effective overpressure. However, PBIs may occur at overpressure lower than the specified threshold depending on the individual orientation and/or the proximity of reflecting surfaces.[10] It can be noted that the auditory system is the first to be damaged due to the blast wave overpressure, see Fig. 7. This is illustrated by the lowest injury threshold of 35kPa[15,16] as shown in Fig. 7. The overpressure of the onset of 100% eardrum rupture is approximately 205 kPa, which does not depend on the duration of the positive phase.[17,20] Meanwhile, the 50% risk of mild brain hemorrhage is about 145 kPa.[33] Figure 7 also illustrates that the ears are most at risk, followed by the lungs and brain. It is worth mentioning that the overpressure threshold for brain haemorrhage has not yet been defined in the evidence-based literature.

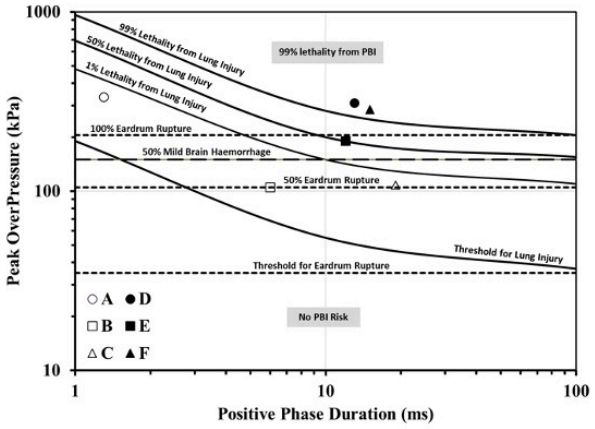

Fig. 7. Expected risk of primary blast injuries (PBIs) at each probe location (represented by markers) plotted against the graphical PBI criteria presented by Denny et al.[10] (represented by solid and dashed lines).

The graphical representation of Denny *et al.*,[10] establishes a framework that can be used to estimate the risk of primary blast injury for specific gauge locations. The markers on the graphical representation in Fig. 7 indicate the expected primary blast injury risk for the predicted peak overpressure at each gauge location, as calculated by the present simulations. According to Fig. 5, prayers most vulnerable to PBIs are located close to the source of the explosion, where the overpressure is at its highest level. The explosion creates a peak overpressure of 335kPa that the Imam and prayers next to him cannot tolerate (probe A), posing a 100% risk of eardrum rupture and a 50% risk of a mild brain haemorrhage. Prayers in the centerline of the mosque, represented by probes B and C, have a risk of 50% eardrum rupture. Moreover, the prayers in the three locations mentioned above (i.e. A, B, and C) are susceptible to minor lung injuries but there is less than a 1% risk of death, Fig. 7. The risk of PBIs for prayers close to the reflecting sidewalls (i.e. probes D, E, and F), especially at the corners, is high due to the high overpressure resulting from the reflection of the blast wave off the walls as well as the longer duration. Prayers close to the mosque corners (probes D and F) are subjected to 100% lethality from primary blast injuries. However, people in the middle sidewall position (E), which is less severe than the corners, have a fatal condition of about 100% ruptured eardrum, and 50% lung and brain injuries. Although the peak overpressure at probe C (108kPa) is the same as at probe B (105kPa), the prolonged positive phase duration at C increases the likelihood of death due to lung injury, see Fig. 7.

5.3. TERTIARY BLAST INJURIES (TBIs)

TBIs are caused by the aerodynamic force generated by blast wind moving after the blast wave. The flow of gusty wind air causes a person to become unstable and fling them vigorously with such force that they crash into hard or sharp surfaces. Referring to the metric of the Fujita Hurricane Scale (FHS) links different wind speeds to the risks of expected damage to infrastructure.[25] The maximum blast wind speeds at the considered locations A, B, C, D, E, and F shown in Table 1 are scaled with the speed, description, and possible damage of the FHS categories. As shown in Table 1, the highest maximum speed of 1467km/h is recorded at the Imam's location, A. The order of locations according to the peak wind speed is A, E, B, D, F, and C. As noted, the effect of wind does not depend only on the distance from the center of the explosion, but also on how the blast wave propagates. The lowest moderate wind speed at location C is about 141km/h, which may lead to the loss of human life[23] and material damage to infrastructure.[25] On the other hand, the successive rows of prayers act as human buffers against the influence of the wind and thus reduce its effect. Unfortunately, this was not taken into account in the study.

5.4. SECONDARY BLAST INJURIES (SBIs)

This type of injury is indirectly related to the influence of strong winds that carry flying debris, bomb fragments, and harmful objects that may kill the prayer. Reports on terrorist mosque incidents indicate that the explosive devices used were hand-made, often filled with materials that could be used as shrapnel to increase the number of casualties.[28] On the other hand, the design of mosques is characterized by large areas surrounded by high glass walls with a few small windows, so secondary injuries resulting from broken glass are expected to be minimal.

5.5. QUADRANT BLAST INJURIES (QBIs)

Quadruple blast injuries (QBIs) are caused by factors other than the three categories mentioned previously. It can include crowding, crushing, burns, breathing problems, exacerbation of chronic diseases, and failure to obtain timely medical care. Injuries and even death during the process of cleaning up and removing rubble after an explosion can be considered QBIs. Mosques can accommodate hundreds of prayers, especially during Friday prayers, and often do not have a sufficient number of emergency exits to ensure safety and environmental health. In addition, mosques are equipped with highly flammable carpets, which are a large source of smoke and toxic fumes resulting from fire. For these reasons, QBIs can be very severe.

6. CONCLUSIONS

This work is valuable for those interested in risk mitigation risk assessment, and preventive building design from explosions, as well as to clinicians who seek to determine blast load conditions for injury safety limits. Computational fluid dynamics has been successfully used to investigate explosions in a confined mosque. The inviscid Euler equations are numerically solved by a finite volume method using Ansys Fluent. Dynamic mesh adaptation to coarse initial cells has proven to be suitable for predicting qualitative and quantitative flow features. It can be assumed that the explosion occurred as a result of the explosion of a 1.15*kg*

Table 1. Peak wind speeds for the assigned probe locations, compared with Fujita Hurricane Scale.[25]

Probe		Fujita Hurricane Scale		
#	Peak Speed	Speed (km/h)	Description	Example of damage
A	1467	>420	Incredible	Cars thrown
B	667	>420	Incredible	Cars thrown
C	141	116-180	Moderate	Roofs partially removed
D	356	332-418	Devastating	Homes leveled
E	695	>420	Incredible	Cars thrown
F	323	332-418	Devastating	Homes leveled

TNT bomb. This is the weight of a typical bomb for a light explosive belt that a person could carry maliciously. The explosion occurred in the first row, one meter behind the Imam. The parameters of the blast wave produced are estimated at a $0.5m$ stand-off distance. The results were analyzed using flow visualization, schlieren, and contours. A history of overpressure and speed was recorded at several locations around the mosque.

The location closest to the explosion center (probe A) records the highest peak overpressure and wind speed. Near the sidewalls record high overpressure with long wave duration due to reflection. However, the corners of the mosque (probes D and F) have the second-highest peak overpressure. The probes pass along the center line of the mosque (probes B and E) and experience the second-highest peak wind speed. Whereas location C near the mosque entrance records the lowest peak overpressure and wind speed. It can be concluded that prayers located near the corners of the mosque are the most vulnerable to inevitable death from primary blast injuries (PBIs). Although the peak overpressure is the highest at the Imam probe (A), but the short duration of its positive phase makes the death of the Imam uncertain by PBIs. However, what is certain is that the Imam and those next to the bomb carrier will die from tertiary blast injuries (TBIs) caused by the blast wind force.

The implications of the present research findings will provide scientific material for increased awareness and education among the public, engineers, and healthcare professionals to prevent and prepare for these patterns of health impacts from explosions.

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