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Dynamic Process and Damage Evaluation Subject to Explosion Consequences Resulting from a LPG Tank Trailer Accident

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Abstract: The involvement of liquefied petroleum gas (LPG), which is highly combustible and explosive, greatly increases risk in road transport. A 3D numerical model was conducted in FLACS, which depicts the dynamic process and variation of combined effects along the multi-directions of LPG explosion under an actual case. With the simulation of scenarios, power-law explosion and fireball models were used to reproduce the results, and the dynamic evolution of specific parameters during the LPG explosion process was analyzed. The results reveal that the LPG explosion's expansion around the expressway moved along the spaces between obstacles, while conditions at the site of the accident had an enhancement effect on LPG/air mixture accumulation. The propagation trajectory of the shock wave in the horizontal direction presented a regular circle within 623.73 ms, and the overpressure was enough to lead to extensive damage to surrounding structures. Further, shock wave-driven overpressure brought hazards to buildings further afield with multiple peak values. The influence of the LPG explosive fireball evolution is significantly reflected in the injury range of the heat flux; the maximum diameter of the on-site fireball eventually extended to 148.19 m. In addition, the physical effect indicated that the turbulence intensity induced by the surrounding buildings in the accident site significantly promoted the interaction between the shock wave and flame propagation. This research proposes a detailed analysis of damage coupling characteristics caused by an LPG tank trailer explosion integrated with a FLACS-mirrored model, which are useful for blast-resistant design and disposal planning under similar accidental circumstances.

Keywords: process safety; shock wave; heat flux; propagation trajectory; explosion consequence

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1. Introduction

Liquefied petroleum gas (LPG) tank trailers are vessels of a certain capacity used for carrying large amounts of LPG for filling or mobile use purposes. Unfortunately, such a mode of transport on urban roads carries potential risks, as the number of accidents shows an increasing trend year by year. LPG transport accidents have occurred in China, Italy and elsewhere in the world, and awareness of the risks from fuel transport activities is increasing. LPG tank trailer fires or explosion accidents can lead to serious consequences. Even if all conditions are normal and all safety precautions are considered in design and operation, there is still a domino risk of accidents occurring during the LPG road transport process [1–3]. Once the LPG tank trailer fails in the expressway, the LPG will undergo a rapid depressurization process. It is noticed that the leaked LPG will gather in the depressions of the ground, which becomes a highly risky zone for the safety of the road transport [4]. In the LPG dispersion process, it is found that the ventilation factor is the key to reducing fire or explosion risk in buildings [5]. The meteorological conditions at the moment of the accident in the area where LPG dispersion occurs before ignition, especially the presence of obstacles (buildings, cars or trees) lead to a cloud footprint different from that expected in free-field dispersion [6]. The characteristics of LPG dispersion near the ground show significant concentration differences in the longitudinal area. These characteristics affect the propagation range of the shock wave, which is reflected in the variation of overpressure with distance [7]. LPG expansion near the ground occurs along the gaps between structural congestions, while continuous large-scale congestion has a significant enhancement effect on LPG expansion and concentration accumulation [8]. LPG tanks are exposed to fires for research to support the prevention of catastrophic scenarios [9–11]. It is of great importance to analyze the flame and overpressure caused by LPG/air explosion, and mainly study the coupling relationship among the flame structures and propagation [12]. The higher horizontal wind speed leads to a stronger convection effect in horizontal direction, resulting in flame height decrease with the elevated flame tilt angle [13]. Another way that the LPG explosion can occur is through the formation of a huge fireball, which produces a strong thermal radiation effect to its surroundings [14–16]. The potential LPG BLEVE and fireball result from ignition of the flammable mixtures of vapor, aerosol, mist, and methane. The evolution of a fireball from an LPG explosion is a dynamic process which involves three stages [17]. When an LPG explosive fireball rises from the ground into the air, it can cause skin burns to people around it, set fire to building materials, and even cause larger accidents [18–20]. It is essential to estimate as accurately as possible the thermal hazards posed by these fireballs that could cause damage to humans and objects on the site of an accident. According to the shock wave theory, the shock wave propagation of LPG explosion is greater than the sound speed, and much larger than the velocity of airflow [21]. The C-J theory proposes that the detonation front is regarded as an ideal strong discontinuity surface without thickness, which is the overlap of the pressure wave front and flame front [22]. When the shock wave passes through, the LPG explosions are immediately transformed into detonation products and release chemical energy. The overpressure–time relationship shows alternating positive and negative changes due to shock wave reflection between the ground, vehicles and buildings. The thermo-mechanical effect of explosion shock-flame interactions [23–25] should be considered in the multi-stage evolution of damage under the changing conditions of the LPG explosion process. These studies have addressed valuable discussion on the unvented and vented LPG dispersions and explosions. However, a damage evaluation from the actual accidents is an integrated whole composed of various factors, and the complex dynamic interactions generate between the explosion source and surroundings under LPG road transport. The previous studies of a single factor simplify the above-mentioned problems and cannot fully demonstrate the dynamic process of structural damage and personnel injuries, so further work is needed for this aspect of research.

Using an actual case of accident and associated chain-reaction events, the process analysis of flammable vapor-liquid phase dispersion and explosion during LPG pressurized tank failure is conducted. Taking into account the influence of the combined action during an explosion, this work aims to perform a systematic analysis of LPG explosion cases on expressways to various parameters, such as peak overpressure attenuation, rate of pressure rise, destruction distance, heat flux distribution, impact and scope of thermal hazards caused by the explosive fireball. By using a CFD-based tool, the extended research focuses on the various conditions of accidental damage in the computational scene models. This work develops an in-depth investigation on dynamic process from the expressway transport accident related to the LPG tank trailer. The relevant data collected by the computational process are adopted and reconstructed for an actual accident scene with various configurations, conditions, geometries and consequences for the accident-induced damage. Current results indicate that the turbulence intensity caused by surrounding obstacles significantly promotes the shock wave propagation process, with a rate of pressure rise of over 100 Pa/ms, which indicates that shock wave strongly effects buildings in a very short time. The heat flux induced by the explosive fireball increases as the LPG load mass is grows, and the rate of temperature rise grows more slowly than the peak rate of pressure rise. The given criteria are addressed in order to obtain realistic considerations of the damage evaluation in this case. Furthermore, the emergency planning for the dynamic process and characteristics should pay special attention to damage sequences that take place in similar accidents.

2. Case Analysis and Numerical Method

2.1. Case Analysis

On 13 June 2020, an LPG explosion occurred on the expressway leading to Wenling city of Zhejiang Province, China. A traffic accident occurred in the vicinity of LPG tank trailers, forming a domino effect of accidents. In the initial event involving an LPG tank trailer driving on the expressway, it affected more objects nearby and stimulated unconventional behaviors. The accident induced fuel release, gas/liquid dispersion, mixtures fire, vapor cloud explosion or even toxic gas poisoning. The accidental events generating the damage of the initial LPG pressurized tank are analyzed using the computational method and models, and the core evolution process is developed with the time lapse by TNO's discretization [26]. The domino effect was brought about in the failure of LPG tank trailer and other nearby facilities, resulting in a serial chain of events with greater impact scope and extremely serious damage. Because of the expressway road status, drivers' mistakes, vehicle anomaly or ambient conditions, traffic accidents such as scraping, overturned vehicles and collision occurred between vehicles, pedestrians, and fixed objects during the transport of the LPG tank trailer. Figure 1 shows the whole process of LPG leakage and explosion after LPG tank trailer failed. It can be found that a gas leakage occurred on the accident site, which was similar to white mist. Due to the high internal pressure of the LPG tank, the leaked LPG dispersed in the accident area. At the initial stage, the gas had a high concentration and formed a cloud-like dispersion pattern, as shown in Figure 2b,c. As the leakage time gradually increased, the gas concentration in the accident area was gradually diluted due to the effect of ambient wind speed. LPG was characterized by heavy gas, and began to spread downwind along the nearby ground. As the LPG pressurized tank's internal temperature was much lower than the ambient temperature in accident area, it caused the leaked medium to change from white mist to colorless gas quickly. The gas cloud could not be detected, but the risk of explosion was great. As shown in Figure 2g, the spark at the bottom of the vehicle ignited the gas, and the vapor cloud exploded instantly. The explosion caused by the vapor cloud was so fast that the fire spread westward due to ambient winds. Table 1 shows the material and characteristic parameters related to the LPG tank trailer that exploded.

Figure 1. Accidental chain of the LPG tank trailer failures and explodes in expressway transport.

Figure 2. Catastrophic consequences caused by LPG tank trailer explosion in expressway.

Table 1. The parameters of the LPG tank trailer in present accident case.

Tank Size (m)	Pressure (Pa)	Diameter (m)	Weight (kg)	Capacity (m^3)
13.23 × 2.64 × 4.05 Length × width × height	1.61×10^6	2.525	26,000	61.9

In the explosion accident caused by the LPG tank trailer failure, 25 people were killed, 24 seriously injured, and the direct economic damage reached USD 14 million. The remarkable overpressure and shock wave-induced impulse of the explosive products impacted the vessel's internal wall of LPG tank trailer, causing the metal tank to deform. Figure 2 showed that the shock wave directly affected the expressway ground from the LPG tank trailer accident site, resulting in serious damage. The LPG tank trailer's vessel was thrown several kilometers away by the explosion and was found severely crushed and deformed. With the propagation of shock wave, the LPG tank and pavement structure cracked and produced debris. As the explosion expanded the air, the explosive fragments attained a high speed in the process, and these fragments flew around the area of the explosion accident irregularly. When the fragments blew apart, the fragments also accelerated under the pressured action of explosive products. LPG leaked into instantaneous combustion, which was bound to produce a fireball. The fireball transmitted the heat flux to surroundings instantly, which led to the transfer of the thermal effect that posed harm to humans and structures. With the high temperature generated by the explosive fireball, a large number of vehicle windows burst due to the burning heat. Residential buildings near the explosion area were severely damaged, and the front of the building closest to the explosion site was completely destroyed. Residential buildings were affected by the shock wave, and glass areas and other structures were damaged to different degrees. Because the shock wave had a wider impact, the glass doors of residential buildings along the street were directly and completely shattered. The building located on the southwest side of the accident site, collapsed due to the impact of the flying tank. The guardrails on both sides of the expressway were completely destroyed. The fireball's high temperature caused injury to surrounding people who had not been successfully evacuated, resulting in burn injury to people within a certain range.

2.2. Numerical Procedure

2.2.1. Governing Equation

In the current numerical process, a computational method is adopted in this research. FLACS is an industrial based CFD tool which can be used to reconstruct the accident scene. These complex scenes feature gas leakage, gas dispersion, self-ignition of flammable materials, combustion, and accidental explosion, etc. The cornerstone of FLACS is a set of fundamental governing equations of fluid dynamics, which contain the mass, momentum and energy equations. As a commercial CFD code, FLACS can be applied to model the process of release, dispersion, combustion or explosion of gases, liquids and vapor cloud in unconfined and confined spaces. The computational tool includes a 3D CFD code that solves Favre-averaged transport equations for the mass, momentum, enthalpy, turbulent kinetic energy, rate of dissipation of turbulent kinetic energy, mass fraction of fuel and mixture fraction on a structured Cartesian grid using a finite volume method. For the actual accident scene in the current research, the process of LPG release and explosion caused by the expressway accident follows the rules of the governing equations.

$$\frac{\partial}{\partial \mathrm{t}}(\rho\delta) + \frac{\partial}{\partial x_j}\left(\rho u_j \delta\right) = \frac{\partial}{\partial x_j}\left(\rho \Gamma_\delta \frac{\partial \delta}{\partial x_j}\right) + S_\delta \tag{1}$$

where, δ is general variable; ρ is density, kg/m^3; Γ_Φ is dispersion coefficient of general variable ϕ; S_Φ is the source term of LPG; u_j is the velocity component in j-direction, m/s; i and j are directions of coordinates.

According to the flame evolution induced by LPG/air mixture combustion and explosion, the governing equations involved in FLACS program include mass conservation, momentum conservation and energy conservation equations. The specific equation of conservation of mass can be shown as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \tag{2}$$

Conservation of momentum:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

Conservation of energy:

$$\frac{\partial}{\partial_t}(\rho E) + \frac{\partial}{\partial x_j}(\rho u_j E) = \frac{\partial}{\partial x_j}\left(\Gamma_E \frac{\partial E}{\partial x_j}\right) - \frac{\partial}{\partial x_j}(P_0 u_j) + \tau_{ij}\frac{\partial u_i}{\partial x_j} \tag{4}$$

where, Γ_E is the turbulent dissipation coefficient; E is specific internal energy, J/kg; τ_ij is the viscous stress tensor produced by molecular viscosity and applied to the surface of microelements; x is the spatial coordinate; t is the time coordinate; and u is the fluid velocity, m/s.

The LPG from the pressurized vessel was released rapidly, and dispersed around the near ground or in the air due to the turbulence intensity induced by wind conditions and obstacles. Based on this, it can be explained by the quantitative dispersion rate as in the following expressions.

$$\Gamma_E = \mu t \cdot \sigma^{-1} \tag{5}$$

$$\mu t = C_\mu \rho \kappa^2 \cdot \varepsilon^{-1} \tag{6}$$

where, μ is dynamic viscosity in turbulent flow, N·s/m^2; ε is the turbulence kinetic energy dissipation rate, m^2/s^3; C_μ is a constant of the turbulence model; σ is the Prandtl number in the turbulent flow; and κ is the turbulence kinetic energy.

$$E = C_P T + m_{fu} \cdot H_c \tag{7}$$

where, H_c is standard enthalpy change of combustion, kJ/mol; Y_F is mass fraction of LPG.

2.2.2. Case-Based Modeling

A 3D model is constructed based on the Wenling expressway explosion accident scene in China, as shown in Figure 3. The geometry model aims to reconstruct the scene according to the actual accident, including the expressway, LPG tank trailer, path, residential houses, vehicles parked on the side of the expressway, the surrounding environment, etc. The materials involved in the LPG tank trailer model are set as mixtures of propane and butane. In this numerical model, there are 89 monitoring points (MPs) set in the accident scene reconstruction model. The MPs can collect the required data of overpressure and temperature data in real time during the simulation process. Since the LPG tank trailer leakage and explosion accident scene occurs on an expressway road, 4 rows of MPs are set in FLACS along the X-Y horizontal direction in the shape of an "m", with a total of 80 MPs, as shown in Table 2. The MPs in row 1 are in the same direction from northeast to southwest. The marked MPs range from 1 to 20. The second row of MPs is perpendicular to the direction of the mountain in the upper middle part of Figure 3, marked as MPs 21~40. MPs in row 3 are in the same horizontal direction, and the marked MPs range from 41 to 60. The fourth row of MPs is in the northwest to southeast direction, and the marked MPs range from 70 to 89. The vertical MPs layout at the site of LPG tank trailer explosion accident can be observed. With the coordinate (370,128,5) as the center, there are 9 MPs in total, which can be used to collect the transmission form of shock wave and thermal radiation in the air after the LPG explosion.

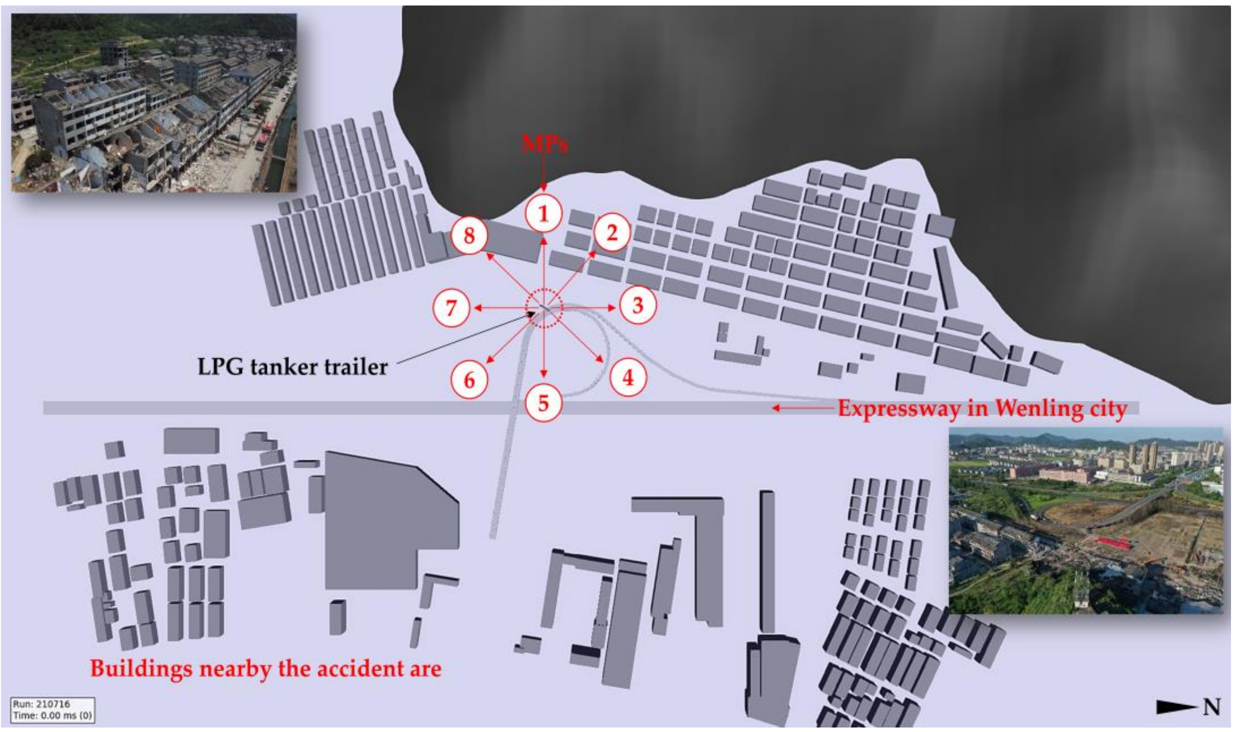

Figure 3. Schematic diagram of the 3D model of the LPG tank trailer accident scene.

Table 2. The positions of MPs are set in the accident scene model.

Serial No.	Flag Number	Position Description
MP 61		In the center of explosion site
MP 62 to MP 69		Vertical line, from the bottom to top
MP 01 to MP 20	6 to 2	Horizontal line, along the northwest
MP 21 to MP 40	5 to 1	Horizontal line, from east to west
MP 41 to MP 60	7 to 3	Horizontal line, from south to north
MP 70 to MP 89	8 to 4	Horizontal line, along the southwest

2.2.3. Boundary Condition

According to meteorological data of the day of the accident, the weather conditions at the time of the accident were clear. The highest temperature on that day was about 308 K and the lowest was over 299 K. The ambient temperature at the time of the accident was 305 K. Wind conditions were south force, 3 degrees. The accident occurred in an area where atmospheric convection was relatively stable. The ambient temperature was high, and the real-time wind speed was 3.4 m/s to 5.4 m/s. The vapor cloud formed by the tank trailer leakage was in the vicinity of the vehicle. Considering the environmental parameters of the accident site in the expressway and the severity of the accident consequences, the ambient temperature was set at 305 K and the atmospheric stability was set at C during the modeling process. The weather data showed that the ambient is south WIND on that day, and the average wind speed of accident place is nearly 5.2 m/s. In this simulation, the boundary parameter of the LPG tank trailer leakage direction is "wind", and the other directions are set as the "Plane-Wave". In FLACS, the initial turbulence intensity was set as 0.1; meanwhile the turbulence length scale is set at 0.01 m. Based on the terrain characteristics of the LPG tank trailer accident in the expressway section, the accident occurred in a relatively obvious bend triangle area with a large slope and a certain dive trend. The mass of the LPG tank trailer in this simulation is set as 48,260 kg, and the actual volume of the substance is 25,360 kg. The leakage site of the LPG tank trailer was located at the front head of the tank body, forming a rupture leakage, and the initial leakage is set as liquid phase leakage. Detailed initial and boundary settings are presented in Table 3.

Table 3. The settings of initial and boundary parameters in FLACS.

Wind Speed (m/s)	Wind Direction	Humidity	Ambient Temperature (K)	Atmospheric Stability
5.2	South direction	88%	305.15	C

2.2.4. Assumptions Used in Simulation

After establishing the FLACS model, this work makes the basic assumptions relating to the simulation process, as shown in the following.

- For the LPG tank trailer in the process of leakage, the leakage rate is set as a constant rate with continuous leakage.
- The air and vapor cloud explosion area is set as incompressible fluid, showing a turbulent state.
- Leaked gas is regarded as the ideal gas, which should conform to the equation of state; it has no chemical reaction or multicomponent in the dispersion process.
- The environment remains the same regarding wind speed and direction.
- The structure is regarded as a rigid body and the influence of fluid-structure coupling is not considered.

2.3. Model Validation

FLACS simulations for processes and predictions of consequences have been developed continuously since 1980, and a series of experiments have been conducted for exposure to thermal hazards [27–30]. The previous research studies are useful to validate the results for the flammable gases, gaseous mixture dispersion, flame propagation and explosion consequences. In our work, a comparison between the experiment [31] and our present 3D model is carried out and analyzed, which aims to investigate the combustion and damage characteristics with the explosion process in a confined space. In the previous experiment, a total of six types of conditions are set in the different scenes. Based on the experiment, the six scenes are selected in FLACS, with variable vent geometries accordingly. These conditions account for the different ventilation factors, vent dimensions and vent aspect ratios. According to the experimental data, five types of fire source with elevated heat release rates (HRRs) are compared with computational schemes. MPs are in accord with the experiment condition. Figure 4 shows the variation of flame height induced by the vertically ejected fire in different scenarios. The solid points represent the experiment data, while the hollow points represent the FLACS data, respectively. It can be obviously observed that the variations of flame heights change with HRRs from the fire source when the vent sizes change. The excessive flammable gas ejects outside of the confined space, resulting in the flame heights induced by the ejected fire increasing with the enhancing HRRs. Figure 4 presents the variations of flame heights with HRRs displaying different trends for changed vents. The vent sizes under fire and explosion accidents have a remarkable impact on the upward flame height. It indicates that the minimum deviation of the comparison is approximately 1.18%, while the maximum deviation is 7.96%. The average deviation between the MPs groups is 3.61%, which is caused by neglecting radiant heat loss after adiabatic treatment of the computational model. Besides, the previous experiment results are affected by various environmental conditions. The above-mentioned problems have been improved upon in the current model and simulation process.

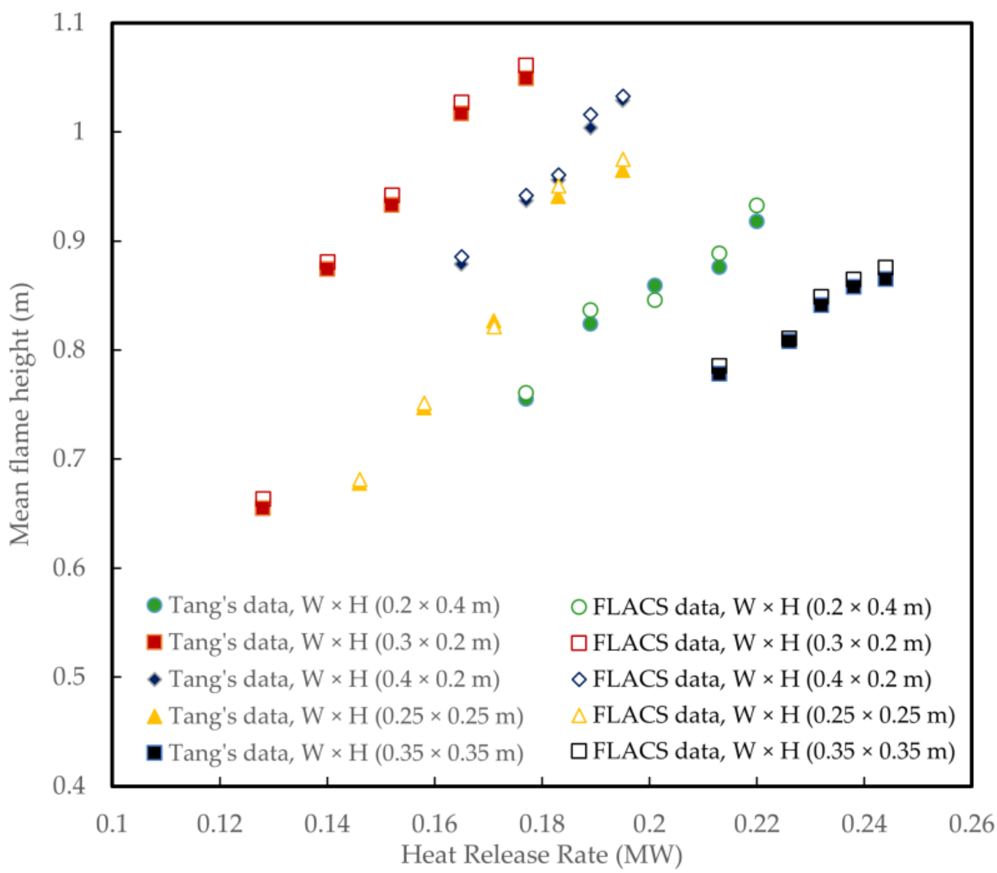

Figure 4. Comparisons between the experiment and FLACS data for model validation.

3. Results and Discussion

3.1. Dynamic Evolution and Characteristics of LPG Tank Trailer Explosion

Once the LPG tank trailer leaks during expressway transportation, the heavy gas dispersion process ensues due to the properties of LPG. The LPG dispersion process can be divided into the initial stage, descending stage, mixing stage and the conversion stage to non-heavy gas. When LPG is ejected from the tank, the vapor cloud will fluctuate and move towards the front of the leakage point under the action of the initial momentum and gravity of the tank. After the initial momentum of the vapor cloud is exhausted, gravity becomes the main force. It causes LPG to begin to fall under gravity, spreading horizontally near the expressway surface. As the LPG vapor cloud disperses, air mixes into the vapor cloud, thus reducing the concentration of the LPG vapor cloud. Through the air flow, LPG vapor cloud exchanges heat with the surrounding environment of the accident area in the movement process, resulting in more air mixing into the vapor cloud. With the passage of dispersion time, more and more air mixes with the LPG vapor cloud in the atmosphere. The mixed cloud begins to transform into non-heavy gas, and the cloud concentration decreases. The final process is the transformation of the LPG vapor cloud from heavy gas to non-heavy gas. Under the effect of atmospheric turbulence, the LPG vapor cloud merges with the air until the density is similar to that of air. The LPG vapor cloud loses its gravitational effect and gradually disperses completely into the surrounding air. When the LPG vapor cloud is ignited, the gas cloud will explode instantly, resulting in a shock wave effect. Although the LPG tank trailer explosion accident site belongs to an unconfined space from a macro perspective, it forms a scene constrained by obstacles due to the presence of vehicles, roads, vegetation and surrounding buildings. Incomplete release of LPG combustion or explosive products leads to pressure buildup. This unbalanced pressure gradient will produce pressure waves. The conduction velocity of the pressure wave produced by the LPG tank trailer explosion is faster than that of the combustion wave. The pressure wave passes the combustion wave and becomes the initial shock wave. Figure 5 presents the shock wave propagation process of the initial explosion of LPG tank trailer on the expressway. The shock wave-induced overpressure experiences an overall and rapid process from peaking to gradually decreasing. The nearly hemispherical wave front forms during the shock wave propagation process, then it quickly expands around. The shock wave reaches the surrounding residential buildings in approximately 899.6 ms. It indicates that the shock wave propagation Is basically consistent with the accident investigation, and the accident site caused by the shock wave in the numerical simulation is consistent with the actual situation.

The top view shows the propagation situation and propagation area of explosion-driven shock wave in the horizontal direction from the perspective of drone. It can be seen from Figure 6 that the propagation trajectory of shock wave in the horizontal direction presents a relatively regular circle. Such shock wave propagation trajectory also reflects the characteristics of no obvious obstacles where the accident occurs. When the explosion of the LPG tank trailer happens, in nearly 623.73 ms, it can be clearly seen from the cloud image that the shock wave at the explosion place is very high. With an overpressure value of approximately 3.0 bar, it is consistent with the actual simulated result. With the explosion time lapse, the shock wave produced by the LPG pressurized tank explosion rapidly propagates to surroundings in the horizontal direction. When the LPG tank trailer explosion occurs over 1050.81 ms, the shock wave has been propagated in the direction of residential buildings on both sides of the expressway. At this time, the overpressure of the shock wave is enough to cause extensive damage to the structures. When the LPG tank trailer explosion occurs at 3524.25 ms, the shock wave has quickly propagated to the long distant buildings. The shock wave-driven overpressure from the LPG tank trailer explosion causes continuous hazards and destruction in the buildings further away.

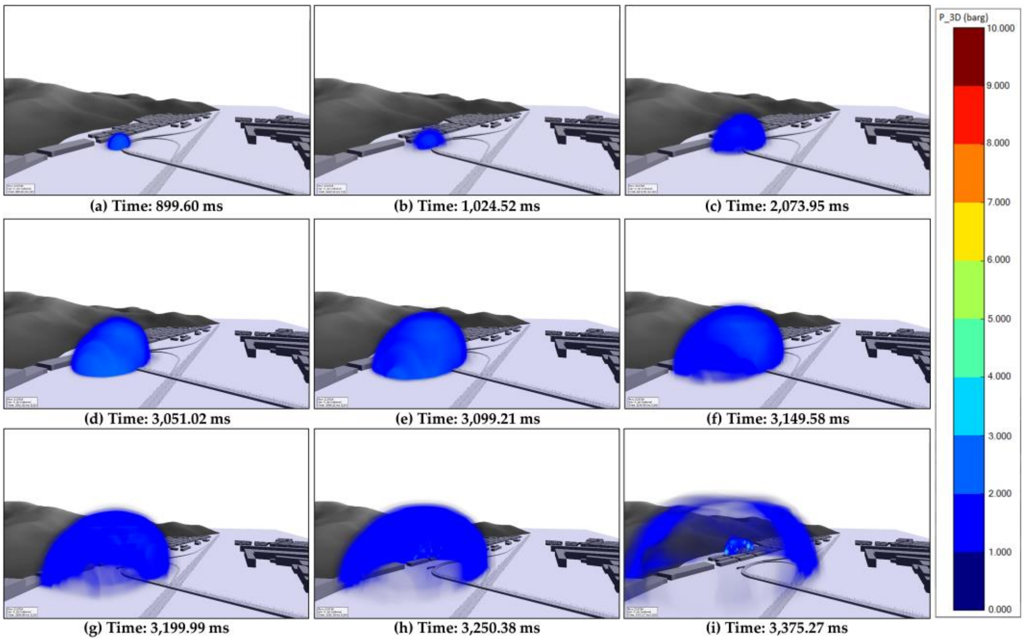

Figure 5. The lateral representation of shock wave propagation during the explosion process.

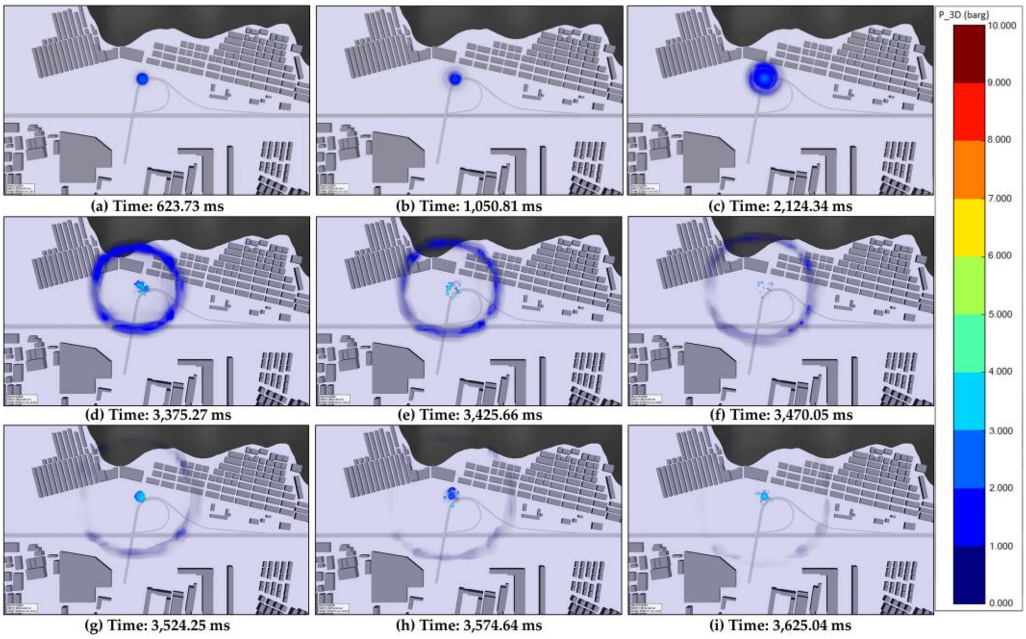

Figure 6. The vertical representation of shock wave propagation during the explosion process.

Figure 7 presents the complete explosion process of LPG tank trailer on expressway. Figure 7a shows the initial explosion of the LPG/air mixture induced by ignition. Since the explosion of the LPG/air mixture has occurred, obvious temperature field changes can be observed at the accident site. Figure 7b–d shows the overall process of the LPG tank trailer forming the explosive fireball after the expressway accident. At this point, the temperature image indicates that the fireball has fully engulfed the entire collision area. This is because the explosive fireball gradually changes from momentum-driven to buoyancy-driven activity as the mass of LPG increases. According to on-site MP data, it is found that the temperature rise rate caused by the LPG explosive fireball has the largest variation range in this period. In Figure 7e–f, it can be clearly seen that the explosive fireball has quickly formed a hemispherical shape on the surface of the expressway. The combustion intensity of the LPG/air mixed vapor cloud inside the explosive fireball rises rapidly, and the explosive fireball radius reaches its maximum on the ground. As the LPG fireball forms on the ground, it begins to lift into the air gradually. The LPG explosive fireball forms spherical size directly above the LPG tank trailer explosion site. The burning flame generated by the explosive fireball appears in yellow and red, and constantly transmits heat radiation to the environment area. Eventually, LPG/air mixture inside fireball is further depleted, and the intensity of thermal radiation gradually diminishes. When the LPG tank trailer explosion takes place in the expressway, the surrounding residents flee in panic after the explosion, and the thermal radiation directly causes burns to people at the scene. The fireball rises into the air to form a complete spherical structure and begins to dissipate. The fireball burns red orange, accompanied by a lot of thick black smoke. The formation and lifting of the LPG fireball are observed from the left and right sides of the expressway. The result shows that the LPG explosive fireball forms a regular half-ball formation near the expressway path and then gradually rises into the air, where the diameter of the fireball is the largest.

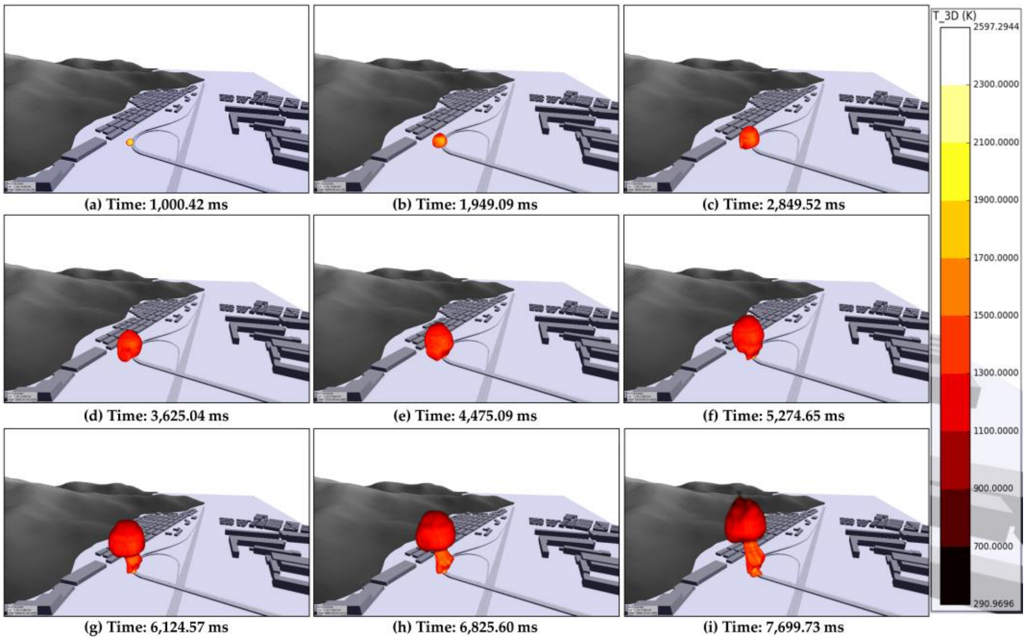

Figure 7. Lateral view of LPG explosion fireball evolution process.

Figure 8 presents the top view of the LPG tank trailer explosive fireball formation process. Figure 8a–i respectively show the changes at the corresponding time when the gaseous mixture from the LPG tank trailer is ignited and explodes until the fireball is lifted into the air. The boundary of the LPG fireball is very regular. The approximately circular area rapidly transmits heat around after the explosion, causing serious damage to building structures and equipment in the horizontal direction. According to the post-accidental investigation and FLACS simulation, the maximum diameter of the LPG explosive fireball onsite eventually extended to nearly 148.20 m. Meanwhile, it is found that the LPG leakage caused a large explosion and created thermal hazards, resulting in extremely serious damage to the built environment around the accident. The road surface at the center of the accident site was deformed and collapsed by the fireball. Since the LPG tank trailer accident occurred on both sides of two large open parking lots, the vehicles were badly damaged. When the explosion fireball forms, the high temperature generated in this area reached more than 2000 K, which has far exceeded the fire resistance temperature of steel structure used for ordinary vehicles. After a certain period of time, the appearance of the vehicles in the parking lot on both sides of the accident has displayed obvious deformation. At a street store far behind the parking lot, it indicates that the canopy above the front door of the store is completely melted and severely damaged.

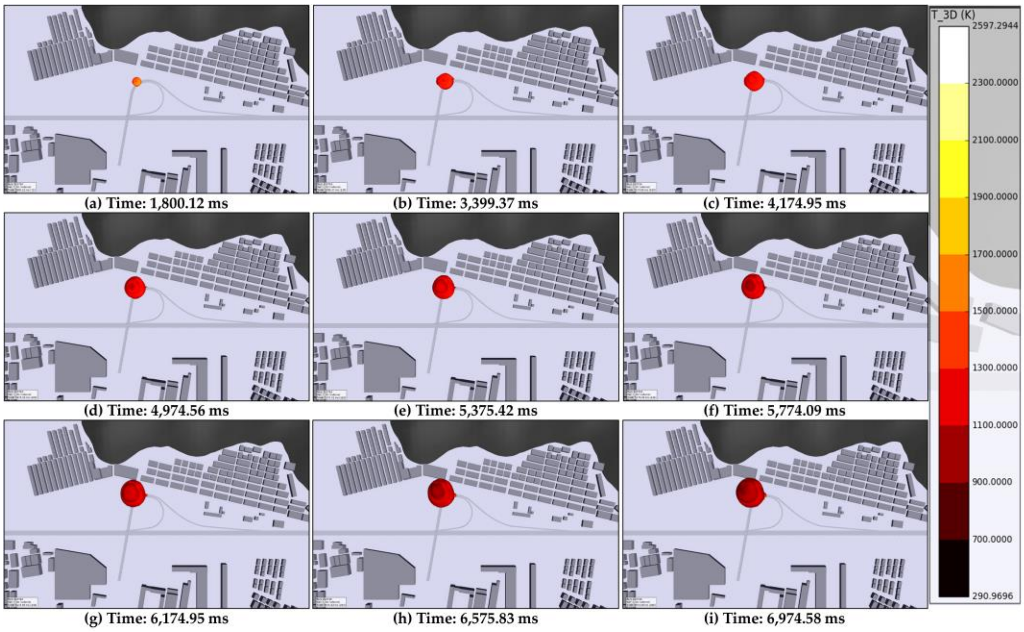

Figure 8. Top view of LPG explosion fireball evolution process.

3.2. Mechanical Damages Subject to Shock Wave Propagation Process

The shock wave-driven overpressure is induced by the initial energy released from the explosion source. More importantly, the damage levels and process safety are evaluated through the shock wave criterion, which determines the accident consequences of the LPG tank trailer explosion [32–34]. The overpressure criterion is adopted to determine the explosion in the expressway section caused by the LPG tank trailer accident. The injury area of the shock wave is the injury area of personnel. In order to estimate the casualties caused by the explosion, the area around the source of danger is divided into the dead zone, serious injury zone, slight injury zone and safe zone. According to the different probabilities of casualties due to explosions, the area near the hazard source is divided into five damage levels from the inside out, including deaths (most people die with overpressure >1.0 bar), serious injury (grievous injury to human organs may cause death, with overpressure from 0.5 to 1.0 bar), moderate injury (eardrum and trachea injury, moderate contusion and fracture, with overpressure from 0.3 to 0.5 bar), slight injury (slight bruising, with overpressure from 0.2 to 0.3 bar) and safety (no injury, with overpressure <0.2 bar). If the personnel in the death zone lack protective equipment, there will be no exception to extremely serious injury or even death. The shock wave generated by the LPG tank trailer accident in the unconfined space impacted the surrounding buildings from all sides in the form of compression and deformed them. The overpressure damage depends on the magnitude of the shock wave, shock impulse, action time of positive pressure and the distance from explosion source. The shock wave-induced overpressure is presented by the related distance, which can be defined as the following expression.

$$\overline{R} = \frac{R_0}{(W_{TNT})^{\frac{1}{3}}} \tag{8}$$

where R_0 is certain range between the explosion source and involved site, m.

The previous studies [35,36] have proposed the relationships between the shock wave and distance, which are based on large-scale experiment data and CFD method of the similarity theories. From Equations (9) and (10), it can be combined with the TNT equivalence method to determine the shock wave and its propagation range caused by the LPG tank trailer explosion.

$$\Delta P_m = \begin{cases} 0.0981 \times \left(\frac{14.0717}{\overline{R}} + \frac{5.5397}{\overline{R}^2} - \frac{0.3572}{\overline{R}^3} + \frac{0.00625}{\overline{R}^4} \right) & 0.05 \le \overline{R} < 0.30 \\ 0.0981 \times \left(\frac{6.1938}{\overline{R}} - \frac{0.3262}{\overline{R}^2} + \frac{2.1324}{\overline{R}^3} \right) & 0.30 \le \overline{R} < 1 \\ 0.0981 \times \left(\frac{0.662}{\overline{R}} + \frac{4.05}{\overline{R}^2} + \frac{3.288}{\overline{R}^3} \right) & 1 \le \overline{R} < 10 \end{cases} \quad (9)$$

$$\Delta P = \frac{0.108}{\overline{R}} - \frac{0.114}{\overline{R}^2} + \frac{1.772}{\overline{R}^3} \quad (10)$$

The inner range of the area is zero, and the outer range is marked as $R_{0.5}$. It indicates that the probability of death due to pulmonary hemorrhage caused by shock wave at the outer circumference is 0.5, and the relationship between it and explosion volume is determined by calculation. Without protection, the vast majority of people in a serious injury area will suffer serious injury, with quite a small number likely to die or suffer minor injuries. The inner range is the death radius $R_{0.5}$, and the outer range is $R_{d0.5}$, which means that the probability of rupturing of the eardrum due to the shock wave is 0.5. Without protection, the vast majority of people in a slight injury area will suffer minor injuries, while a few will be seriously injured or unharmed, with a low probability of death. The range of slight injury area is $R_{d0.5}$ and $R_{d0.01}$. It indicates that the probability of rupturing of the eardrum at the external boundary due to shock wave is 0.01. The vast majority of people in the safe zone will not be injured even if they are unprotected, and the probability of mortality is approximately zero. Moreover, the inner range of the safe zone is the outer range of slight injury area $R_{d0.01}$, and the outer range is infinite. The overpressure from the LPG explosion will lead the destruction of the surroundings in different degrees, including the houses, urban infrastructures and facilities around the explosion source. When the overpressure is over 2.0 bar, it will lead the severe displacement of steel structures and complete destruction. In the serious range, the heavy destruction of anti-earthquake buildings is caused with the overpressure threshold between 1.0 and 2.0 bar. Furthermore, the steel skeleton and the lightweight reinforced concrete buildings are destroyed under 0.5 to 1.0 bar, and the slab-brick buildings (thickness between 0.2 and 0.3 m) are broken without concrete materials with overpressure of around 0.3 to 0.5 bar. Under the moderate level (0.07 to 0.3 bar), the brick buildings are damaged at a rate of 50%, and self-restraining steel buildings are damaged completely. The buildings suffered slight damage and glass is blasted by overpressure between 0.02 and 0.07 bar. If the shock wave-driven overpressure deceases to 0.0196 to 0.02 bar, the glass cracks. Only under the safe level, with an overpressure value less than 0.0196 bar, it brings about non-destructive phenomena [32–34]. Based on the structural evaluation from the shock wave-induced destructive hierarchic, the accidents will cause direct economic losses. The damage degrees of the surrounding buildings are related to types of explosion source, feature of building structures, characteristics of explosion energy, impact distances from accident site and other environmental factors. The LPG explosion-induced overpressure on the shock wave front is associated with explosive energy. The higher energy of the LPG explosion source will promote the higher intensity of the LPG explosion-driven shock wave. Therefore, as a result, the greater the overpressure on the shock wave front accordingly. The shock wave is three-dimensional, which propagates from the explosion source as the center to the open space.

Figure 9 presents the shock wave changing in the time lapse when it propagates in vertical space. MPs 61 to 69 are arranged in the air along the Z axis starting from the center of the explosion source. According to the overpressure data, the MP closest to the explosion source shows the fastest peak overpressure. At nearly 579.02 ms after the LPG explosion, the peak value of shock wave-induced overpressure from the nearest location of the accident source reaches up to 0.489 bar. The pressure rise rate is over 100 Pa/ms, which indicates that the shock wave has the strongest effect on the obstacle in a very short time. The maximum overpressure generated by the shock wave in vertical space is 2.669 bar. According to the threshold specified from shock wave-driven overpressure, when the overpressure induced by shock wave is greater than 2.0 bar, the steel structure has a positive impact and a large displacement, resulting in complete destruction as a whole. Since there is no shelter in the air where the accident occurs, the worst damage caused by the shock wave is located on the expressway pavement. Combined with the accident investigation, it is shown that due to the effect of the shock wave, serious deformation occurred on the expressway pavement, which is a destructive result of the powerful shock wave formed by the LPG tank trailer explosion.

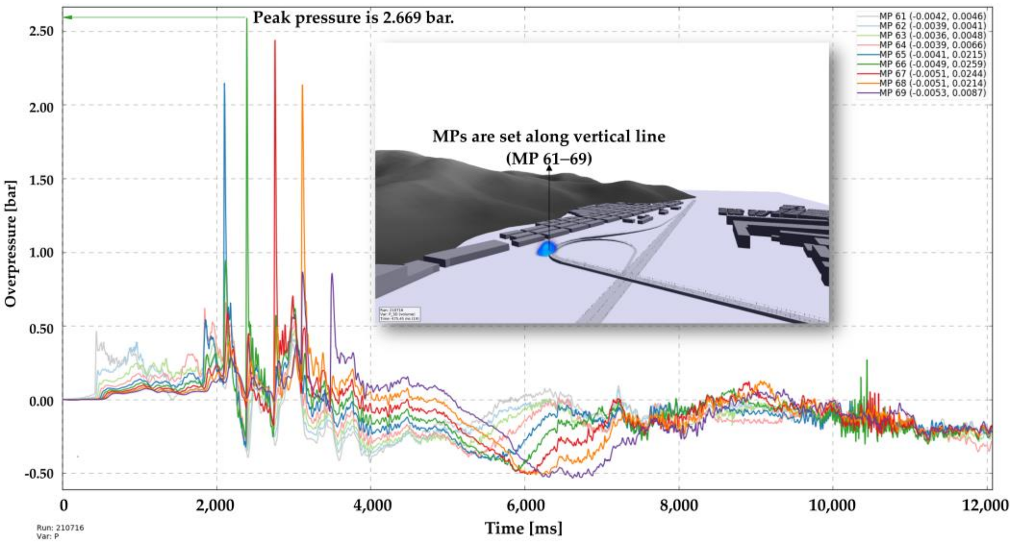

Figure 9. Overpressure from LPG explosion remains in entries vertical to the direction.

Figure 10 presents the change of shock wave generated by LPG explosion when it propagates from the southeast to the northwest area. The overpressure fluctuates significantly in the shock wave propagation process, which can be roughly divided into three stages over time. The first stage is the initial pressure rise period; that is, overpressure changes will occur immediately after the explosion of the LPG tank trailer. The peak overpressure reaches 4.411 bar in approximately 401.93 ms. At this time, the maximum value of pressure rise rate is more than 120 Pa/ms, which indicates that the shock wave produced after the LPG explosion is remarkably fast. Then, the shock wave propagation enters the second stage, which is the period of unstable fluctuation. During this period of time, the shock wave propagation is affected by the obstacles in the path direction, which will produce varying degrees of change. The product of the explosion initially moves at a high speed, and its speed decreases rapidly until it reaches zero due to the constant dissipation of energy. When the explosive product expands to a specific volume (or limited volume), its pressure drops to the initial pressure when the surrounding medium is undisturbed. The explosive product does not stop moving, driven by the action of inertia and excessive expansion, until it reaches a certain maximum volume. At this time, the uniform pressure of the explosive product is lower than the initial pressure when the medium is not disturbed, and the phenomenon of negative pressure appears. In the second stage, due to the occlusion of residential buildings and other structures, shock wave disturbance is formed. So, the overpressure induced by the shock wave begins to decay and then increases rapidly after 100 ms. During this period, the shock wave produces a phenomenon of secondary peak, with a value of 6.191 bar. The third stage is the attenuation period of shock wave. In this process, the shock wave is gradually transferred to the far field, and the energy of the explosive product is gradually exhausted in the process of propagation. The overpressure fluctuation of the shock wave is stable, and the maximum value is maintained between 0.02 and 0.05 bar. Figure 10 indicates that the shock wave can still cause damage to the glass and other structures of residential buildings in the third stage, and the damage range is wide. Figure 11 presents the propagation and variation of shock wave in the east-west direction. As the distance between this area and LPG tank trailer is the nearest, the effect of shock wave is most significant. As can be seen from Figure 11, the peak overpressure exceeds 4.0 bar many times. Based on the threshold analysis in shock wave-driven overpressure, it can be concluded that shock wave in this direction will cause fatal injuries to on-site individuals, and meanwhile, irreversible damage to buildings. Figure 11 shows that the front of the house closest to the explosion source is almost completely destroyed by the shock wave, and the steel structures of the buildings are severely deformed.

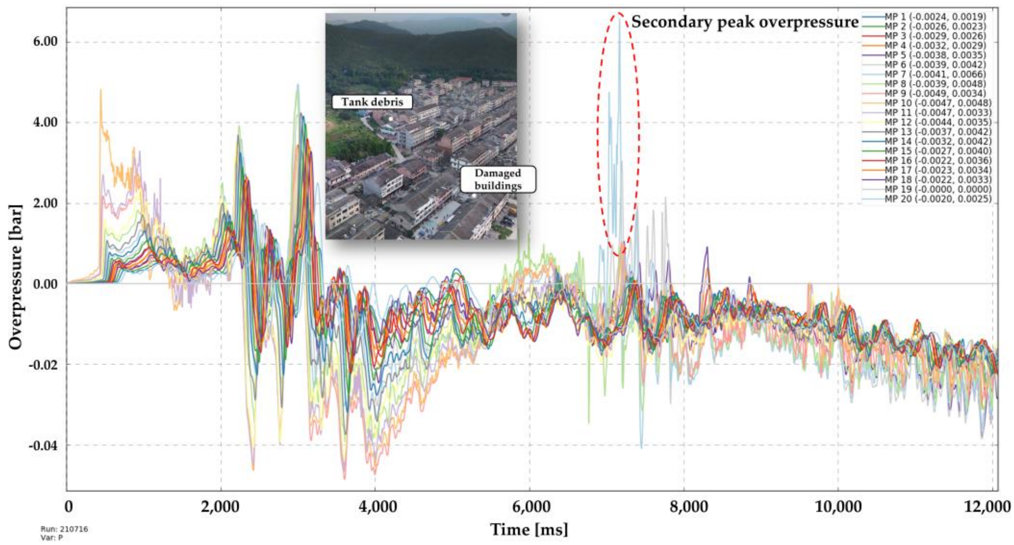

Figure 10. Shock wave changes with time lapse from southeast to northwest (MP 01~20).

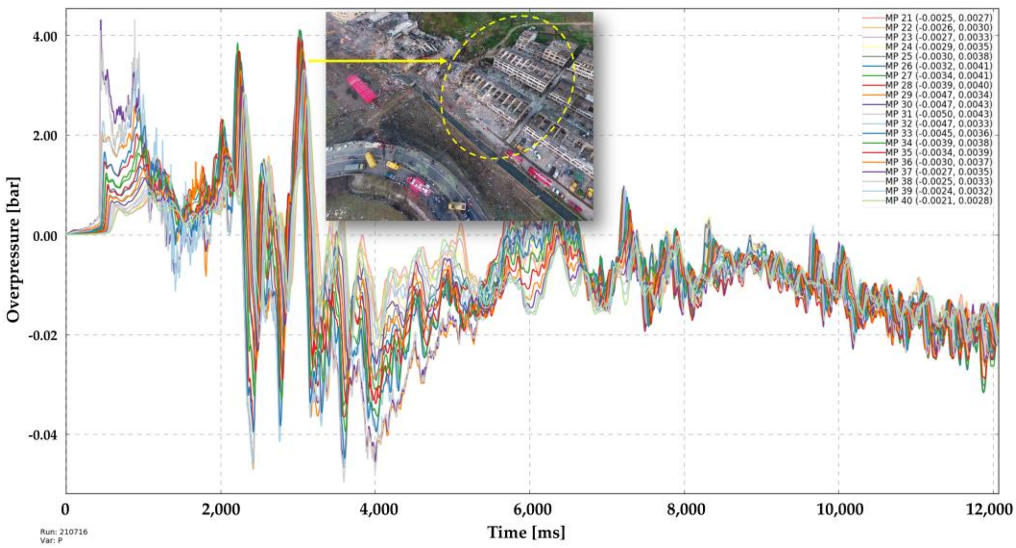

Figure 11. Shock wave changes with time lapse from the east to west (MP 21~40).

Figure 12 presents the propagation changes of shock wave along the southwest to the northeast direction. It indicates that the initial peak value of the shock wave overpressure is as high as 4.623 bar. Combined with the scene of the rescue situation, the area most affected by the explosion is located in the southwest of the accident. Due to the strong effect of the explosion-driven shock wave, the building structure is likely to experience high intensity damage and failure. On the other hand, the LPG tank flies out and hits the roof of the building in the area, resulting in the complete collapse of the house under the above double impact. Figure 13 shows the overpressure change of the shock wave from the south side to the north side. The overpressure strength generated by the shock wave is relatively weak in this direction. This is because there are not many obstacles in the north-south direction of the accident site, which is mainly empty ground. Therefore, the propagation process in this direction is consistent with the propagation law of the LPG explosion-driven shock wave in a large open space. The initial peak value of shock wave overpressure is shown as 1.842 bar, followed by the secondary peak value at 2756.19 ms, which is approximately 3.731 bar. Thereafter, the propagation of the explosion-driven shock wave from the direction between the north and the south areas shows a gradually decreasing trend, and there is no large pressure rise again in its propagation path, which is consistent with the situation in the real accident scene.

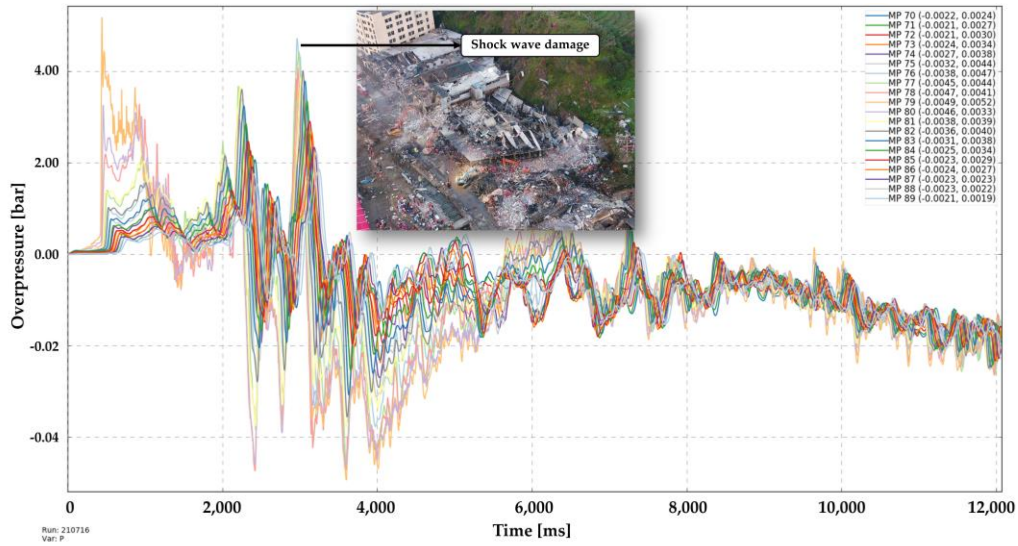

Figure 12. Shock wave changes with time lapse from southwest to northeast (MP 70~89).

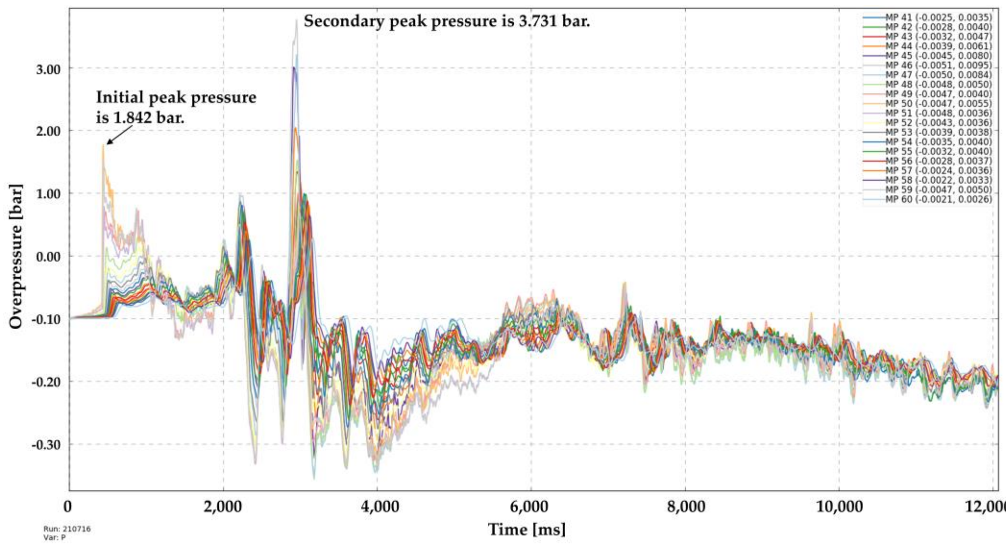

Figure 13. Shock wave changes with time lapse from the south to north (MP 41~60).

3.3. Distribution and Fluctuation of Heat Flux in LPG Explosion Process

In the sudden explosion of the tank trailer of hazardous chemicals, the flame and heat flux velocity are fast around the ground near the explosion source. The transfer scope of the explosive fireball generated by the LPG tank trailer accident is very wide, accordingly. The degree of thermal damage to people and buildings within a certain range can be determined based on the high temperature formed by explosive fireball from LPG tank trailer accident. In this research, the local deflagration and instantaneous high temperature caused by the LPG tank trailer will cause the permanent deformation of local or whole structure in a certain range of expressway. For the buildings far from the LPG accident site, its performance is damaged and degraded by the high temperature of the explosion fireball, which further reduces the safety of expressway and other structures and reduces its function. The damage results can be presented in terms of the probability of death and various degrees of hazard identifications [37–39]. According to the high temperature criteria, it can be examined with different thermal degrees from LPG explosive fireball. When the temperature is over 1003.0 K (Fatal level), it will lead to the spheroidization, austenitization and melting of cementite in containers, tubes and pipelines, etc. In addition, the carbon steel passivation film is destroyed, and the carbon steel undergoes serious mechanical deformation. When the temperature changes between 698.0 and 1003.0 K, the strength and corrosion resistance of containers, pipes, etc. may fail. Meanwhile, the burst of window glass, deformation and creep of carbon steel, and reduced strength of stainless steel may occur under the severe level. If the temperature decreases to a moderate level (478.0 to 698.0 K), it leads to decreases in the strength, hardness and conductivity of pipelines, and a tempering color appears on surface. Furthermore, the melting of window glass, the complete combustion and carbonization of wood, the melting of zinc aluminum castings occur. Under the slight level (338.0 to 478.0 K), the softening of metal surface coating, then foaming and fading of fiber and plastic, etc. occur. In this range of slight intensity, the melting and burning of vinyl coatings, etc., and the carbonization of polyurethane and epoxy resin may occur. Only when the temperature is less than 338.0 K does it lead to no obvious damage. Based on the damage description and its threshold, in the LPG tank trailer accident site, the expressway and buildings structures under the effects of the fireball experienced the problem of structural failure in a short time. Meanwhile, the thermal radiation generated by the explosive fireball also caused different levels of burns to the skin of people at the accident site, and even direct death in serious cases.

Figure 14 presents the changes in heat radiation transfer of fireball from the perpendicular line of MPs collected data. MPs 61~69 are set at the roof of the LPG tank trailer. The MPs have certain separation distances from LPG pressurized tank. In this research, one point for each MP collects the temperature change data. The maximum temperature of the LPG fireball in the perpendicular direction can reach 2287.5 K. The LPG fireball forms a hemispherical shape near the ground for a short time and gradually rises into the air. A spheroid structure is formed in a certain range and finally dissipates because of the depletion of LPG/air mixture inside the explosive fireball. Figure 14 indicates that a time delay exists within the various values of the explosive fireball temperature at different vertical spaces. The temperature rise rate of the LPG fireball in the air decreases with the increase of the altitude from the expressway ground surface. Then, the corresponding time interval required to reach the peak value of the fireball's temperature increases. In the vertical space where LPG explosion occurs, the propagation intensity of thermal radiation is no longer unified with the lapse of time. Therefore, the distribution of temperature field appears irregular fluctuations. It is worth noting that the temperature in the vertical space rises again because the combustible materials remaining in the site continue to burn after the LPG explosion. It reflects the characteristics of the mixed vapor cloud leaking from the LPG tank trailer as a heavy gas in the early stage of the accident. The above-mentioned result is caused by the dispersion characteristics of the concentration difference of the vapor cloud in the vertical space.

Figure 15 shows the changes in the horizontal transmission of the high temperature flame in front of and behind the accident after the LPG fireball formed by the tank trailer explosion. The temperature values monitored by MP 01 to MP 17 indicate that the LPG vapor cloud explosion happens quickly once the LPG/air mixture is ignited. Meanwhile, an explosive fireball is formed in a short time, and the heat flux of the explosive fireball spreads immediately to the front and lateral space from the LPG tank trailer. Nearly

600 ms after the occurrence of LPG VCE, the MPs arranged close to accident site show that the temperature values rise rapidly, reaching the peak temperature with the data of 2289.1 K. Combined with the thermal damage threshold, the fireball temperature is sufficient to result in permanent structural deformation, reinforced concrete meltdown, etc. The video footage from the accident scene indicates that the fence of the expressway has melted due to thermal damage from the LPG fireball. The front structure of the LPG tank trailer has burnt out of shape by the high temperature produced by the LPG fireball. The temperature curve indicates that the temperature rise rate in front of LPG tank trailer is more remarkable than that of MPs behind LPG tank trailer. The maximum temperature in front of the LPG tank trailer reached up to approximately 2308.4 K, which is larger than the temperature detected in the rear of LPG tank trailer. Based on the analysis, this is mainly due to the large amount of accumulation of leaked medium in the front of LPG tank trailer caused by wind conditions. The above-mentioned reason causes the enhancement of thermal radiation intensity from the explosive fireball in the accident area after the occurrence of the LPG vapor cloud explosion.

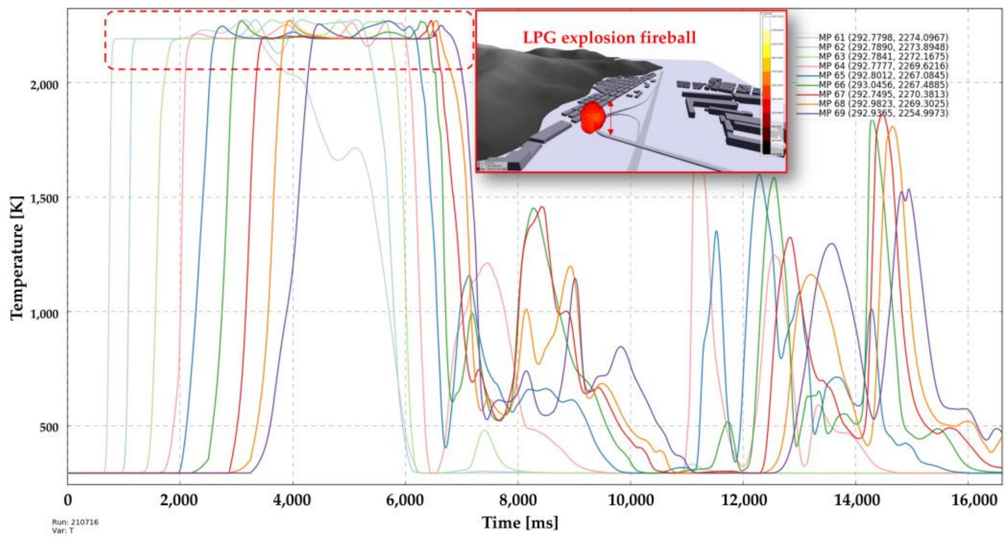

Figure 14. High temperature from LPG explosion fireball releases in vertical space.

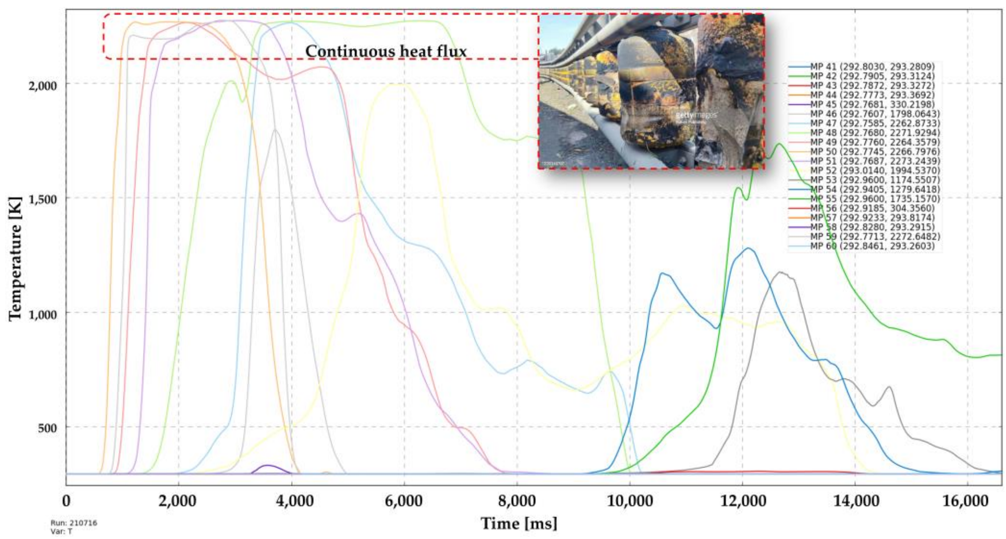

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Figure 15. Heat flux fluctuates with time lapse from south to north area (MP 41~60).

Figure 16 shows the temperature data monitored by MPs from the direction of the southeast to the northwest in accident site. As can be seen from Figure 16, the region close to the explosion source is significantly affected by the thermal radiation of explosive fireball, which is prominently reflected in the change of temperature over time. When the LPG tank trailer explosion occurs, MP 10 near the explosion source shows the fastest temperature rise to its peak value. The initial peak temperature is about 2291.1 K, and the temperature rise rate is over 7.5 K/ms. On the northwest side is a cluster of businesses that is badly damaged by the LPG explosion. As shown in Figure 16, the electric wires and other cables in front of the shop are all ignited and burned due to the effect of the LPG explosive fireball. Figure 17 presents the temperature data collected by the MPs on the east and west sides of the LPG tank trailer accident. It can be observed that the several times of temperature rise are formed after the LPG explosion. This is due to the unconfined car parking area located in the immediate place on the west side of the accident site. In this accident, the parked vehicles were scorched and almost completely destroyed. It can be observed from Figure 17 that the glass window of the car parked on the west side of accident area completely fractured, and the car frame suffered stressed deformation subject to the fireball's high temperature. Many cars experience secondary ignitions and catch fire, and fragments from the explosion fly directly into nearby buildings. Through the temperature curve, it indicates that the temperature in this region presents several fluctuations, and a secondary peak temperature occurs. Figure 18 presents the temperature data collected by MPs positioned in the southwest to the northeast directions of accident site. The maximum temperature of heat transfer by LPG fireball in this region is approximately 2304.7 K. The space in the northeast side is a relatively empty large open space. The thermal radiation from the LPG fireball decreases rapidly in this region, so the increase of temperature data is not obvious. Some buildings are located on the southwest side; there are some buildings here which are affected by the thermal radiation of the explosive fireball. When the LPG explosion occurred, the southwest side of the buildings is quickly ignited, causing a large area of fire. Based on the temperature data, the high temperature lasted for a long time on the southwest side. The region remains over 3000 ms after reaching its peak temperature. It indicates that the thermal radiation transmission in the region encounters obstacles, or causes a larger scale combustion accident. According to the post-accident investigation, the damage effect from LPG explosive fireball has a strong destructive effect on people and the environment around the accident source where the LPG tank trailer explosion occurs, while the effect is significantly weakened in a certain distance from accident site.

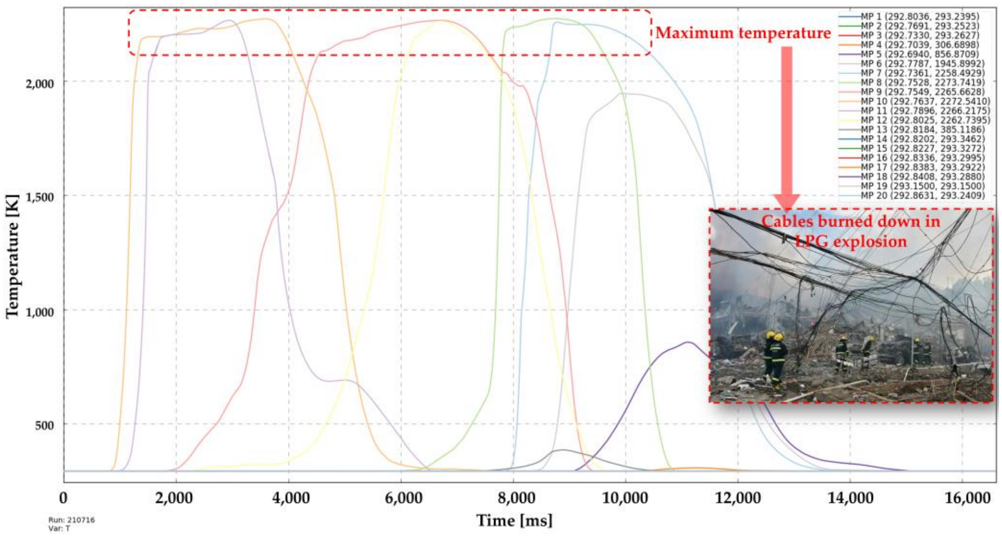

Figure 16. Heat flux fluctuates with time lapse from southeast to northwest area (MP 01~20).

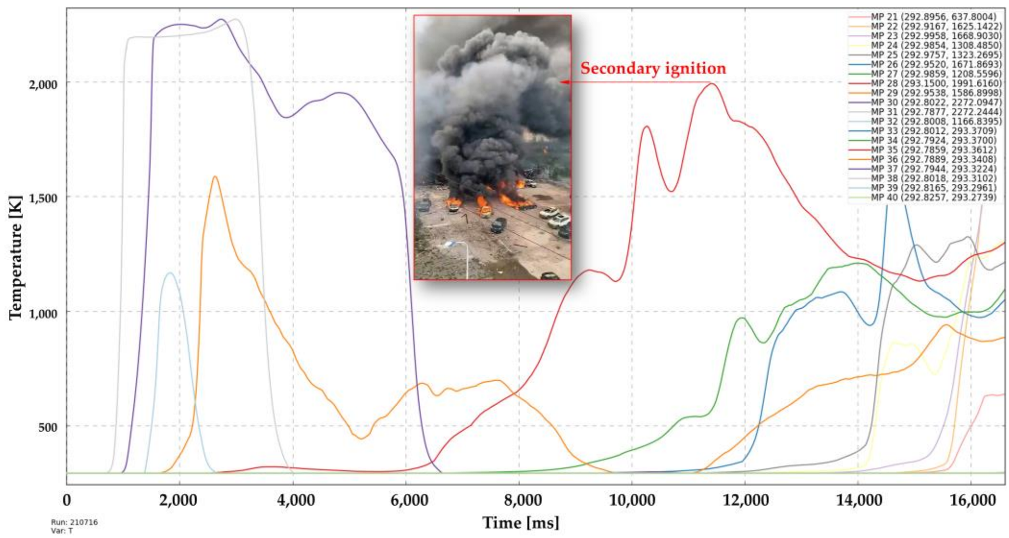

Figure 17. Heat flux fluctuates with time lapse from the east to west area (MP 21~40).

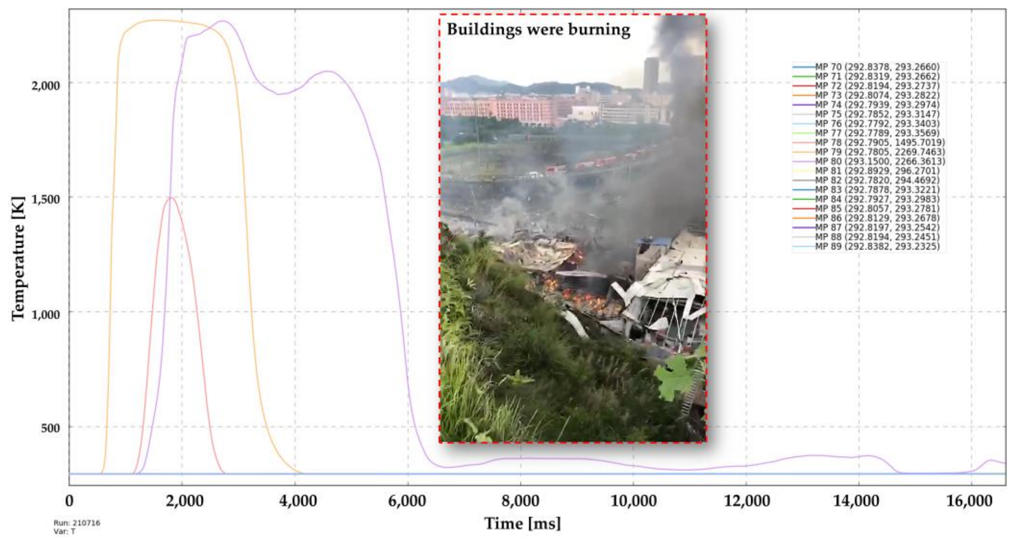

Figure 18. Heat flux fluctuates with time lapse from southwest to northeast area (MP 70~89).

4. Conclusions

This work presents an LPG explosion accident case in detail from an expressway transport process that happened in China. The dynamic process and damage evaluation of the accident sequences are investigated by scene reconstruction in FLACS. The main conclusions are presented as follows.

- Potential explosive energy is accumulated around the circle section of expressway and becomes a heavy gas characteristic of LPG/air mixture dispersion. The LPG explosion's effects on buildings depend strongly on the surrounding arrangement. In this case, the shock wave propagates in the direction of residential buildings on both sides of the expressway. The peak overpressure induced by the shock wave is enough to cause extensive damage to nearby structures.
- The turbulence intensity caused by the obstacles significantly promotes an increase in the shock wave propagation speed. The shock wave reaches the residential buildings in approximately 899.6 ms, within the influence of surrounding obstacles at an elevated block ratio. The pressure rise rate is over 100 Pa/ms, which indicates that the shock wave has the strongest effect on the obstacle in a very short time.

- The radiative heat flux generated by the LPG explosive fireball increases as the tank trailer load mass increases, and the temperature rise rate from heat flux grows more slowly than the maximum rate of pressure rise. The influence of the LPG mass on the evolution of the explosive fireball is remarkably reflected in the damage range of heat flux. The longer the LPG dispersion time takes, the larger the vertical diameter of fireball and the wider range from LPG explosion thermal hazards.
- The dynamic response of cracks on building structures formed by initial explosion intensifies the surrounding destruction of the shock wave energy during the secondary explosion, resulting in a greater damage in shock-wave-driven overpressure on the far-field. In this case of LPG tank trailer explosion, the lethal distance of injury from the explosive fireball is significantly worse than that of overpressure injury, while the damage range from the shock wave is even longer than that of heat flux extension.

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