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Experimental Study on Toxic Agent Dispersion inside a Shopping Centre

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Abstract

Shopping centres are ranked among the most threatened crowded places that may become a potential target of terrorist attacks. This experimental study deals with the release of the chemical warfare agent sarin into the interior of a shopping centre. It describes the dependence of sarin dispersion on the HVAC (heating, ventilation and air-conditioning) system inside a building. Amyl acetate was used as a substitute for sarin as it is a compound with similar physical properties. The experiment was performed in a shopping centre under real operating conditions using a HVAC system. Two experimental measurements were determined. The first scenario was amyl acetate dispersion directly into the sales area, while the second dispersion of amyl acetate was directly into the HVAC unit located on the roof of a shopping centre. The direction and speed of dispersion of the chemical substance in the shopping centre were monitored. Data from the experiments were compared and the more dangerous method of dispersion was determined. Strengths and weaknesses of the HVAC system that determine the spread of amyl acetate are described.

Keywords: amyl acetate; sarin; shopping centre; dispersion; HVAC system.

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1. Introduction

The issue of chemical terrorism has become a fact and is often discussed. The activities of extremist groups have been extensive and the victims of terrorist attacks are often civilians. At present, there are also many other potential threats, such as when the attackers inform about the attack with a dangerous chemical substance in advance in order to intimidate or incapacitate the civilians in public buildings. Chemical warfare agents may be a very effective coercive means against government officials, institutions, various corporations or population groups due to the fact that they are relatively easily made and applied, they are functional even when unclean, they may hit a large number of people and they have a strong psychological effect not only on afflicted persons but also on rescue teams, the public and politicians. History has proved, several times, that the most suitable environmental properties for the misuse of chemical warfare agents are crowded buildings and places. Therefore, it is possible to rank among the most endangered entities the following: places for entertainment (theatre, cinema, stadium, entertainment building), transport hubs (railway station, airport, underground station), shopping malls, public buildings, offices, tourist centres, etc.

The above-mentioned facts have become a springboard for experimental measurements focused on the dispersion of a toxic substance in a public building. In order to carry out the measurement, it was necessary to modify the issue of chemical terrorism to a specific incident. In the theoretical part of the study, the potential scenarios of chemical attack were analysed: a likely toxic agent is sarin (IUPAC ID: (RS)-propan-2-yl methylphosphonofluoridate) [1], which is an organophosphorus nerve agent with high acute inhalation toxicity. The most suitable method for sarin dispersion is simple evaporation or release by pressure [2]. Next, the system of public buildings was analysed and the most suitable building for a chemical attack was chosen. The assessment of various types of public buildings regarding their attendance and frequency was performed. The riskiest type of building was determined to be shopping malls [3]. As for the most convenient place for the dispersion of a dangerous substance, two variants were evaluated. In the first scenario, the place of the dispersion was the sales area in the locality with the highest number of customers, while in the second scenario the toxic substance was sprayed into a suction rooftop unit of a HVAC (heating, ventilation and air-conditioning) system. The scenarios were followed by the experimental part of the study. The objective was to monitor the concentration of a dispersed toxic substance and to evaluate the weaknesses of the safety system of shopping centres. Conclusions of this study cannot be generalized to all shopping centres, because every building has different size and different replacement of ventilation elements. Also a regulation of the incoming air is not similar in all buildings. The results of the study have a practical effect – interviews with the shopping centre managers revealed that shopping centres do not have sufficiently elaborated emergency procedures in case of extraordinary events such as the release of a dangerous substance. The conclusions of the experiment have been conveyed to the management of commercial chains. It is proposed that the assessment of the weak points in security systems of shopping centres will result in an improvement in the system of public building protection.

2. Materials and Methods

The main aim of the experimental measurements was to determine the speed and the direction of the spread of a dangerous substance in an air-conditioned entity. The preparation of this experiment was partly as a result of the data of experimental measurements in the Prague underground and Old Town Square in Prague [4].

2.1. Shopping Centre and HVAC (Heating, Ventilation and Air-Conditioning) System

For the experiment a hypermarket called 3K size (means 3000 m^2 sales area) was chosen. A hypermarket is a type of superstore combining a supermarket and a department store. This type of shopping centre is the most frequent type of shopping centre in the Czech Republic. The studied shopping centre was characterized as a single-floor building encompassing a self-service department complete with several licensed shops with a market lane. The size of the sales area was 55 x 60 m and height 6 m. The proper microclimatic conditions were ensured by a HVAC system formed by two rooftop units, or so-called 'rooftops'. The fresh outside air was brought to the rooftop unit where it was mixed with the inside air from the sales area, distributed into the sales area by the air distribution system, and then circulated by ventilation fans, or so-called 'anemostats', which enable the conditioned air to be distributed into the interior of building. During the experiment, the microclimatic conditions in the sales area were: temperature 16°C, relative air humidity 40%.

2.2. Instrumental Techniques and Chemicals

Within the experiment, sarin was substituted by amyl acetate (IUPAC ID: 3-methylbut-1-yl ethanoate) as a substance that has similar physical properties to sarin, simple detection, bearable toxicity and availability [4]. Selected properties of sarin and amyl acetate are described in Table 1. During the experiment, we applied amyl acetate (n-pentyl acetate, CAS 628-63-7) for analysis: >98.5%, Sigma Aldrich Chemie GmbH, isopentyl acetate <1%, Lot & Filling Code: 1252898 10807295, density 0.877 g/mL at 20^{o}C.

Table 1: Selected Properties of Sarin and Amyl Acetate [3]

Substance	Sarin	Amyl acetate
Molecular weight	140.09	130.18
Colour/Form	colourless liquid	colourless liquid
Melting Point	-56^{o}C	-71^{o}C
Boiling Point	150^{o}C	142^{o}C
Density	1.0887 g/mL (25^{o}C)	0.8756 g/mL (20^{o}C)
Vapour Density	4.8	4.6
Saturated vapour pressure	385.7 Pa (25^{o}C)	533.0 Pa (20^{o}C)

For detection of the spread of amyl acetate, it was necessary to use devices that are able to continuously monitor the concentration of a specific chemical substance. For experimental measurements, we used portable VOC (volatile organic compound) gas monitors: MultiRAE Plus, MiniRAE 3000 and ppbRAE 3000 (RAE Systems, USA). All the instruments were calibrated prior to the experiment on an exact concentration of calibration mixture of amyl acetate vapour in air. For calibration, a dynamic calibration unit: SYCOS – K DPG (Ansyco, Germany) was used. Photoionization detectors have a self-cleaning function; after the first experiment, they were self-cleaned in an uncontaminated environment and then used in the second experiment. For the detection of amyl acetate, we used not only detection appliances but also individuals who detected amyl acetate by smell. The approximate value of smell threshold for amyl acetate was set at 10 ppb for an individual [5]. Determination of smell threshold of tested people is shown in Table 2. Detection points for detectors and individuals were distributed evenly in the sales area, next to the main entrance/exit and on the roof of the shopping centre.

Table 2: Determination of Smell Threshold of Amyl Acetate, Number of Tested People: 10 [5]

Concentration of Amyl Acetate (ppb)	Positive Smell Detection (Number of People)	Negative Smell Detection (Number of People)
2	0	10
5	1	9
10	8	2
20	8	2
50	10	0
100	10	0

2.3. Scenarios

Two experimental scenarios of a toxic substance dispersion were accomplished: a dispersion in the interior and a dispersion from the exterior. The amyl acetate substance was in both cases released by pressure with nitrogen as the carrier gas. The amount of dispersed amyl acetate was 200 mL for each scenario, which was dispersed in 40 seconds. The detection of amyl acetate was carried out continually for 30 minutes with the values recorded every 30 seconds. Emergency exits were opened 10 minutes after the dispersion, while the main entrance/exit was open during the entire time of the measurements. Emergency ventilation was not switched on because it was not possible to start it within the time of the experiment. The experimental conditions were, as far as possible, similar to real conditions, imitating a shopping centre in rush hour when people are permanently flowing in/out of the building.

Scenario 1 was performed in the interior of a building near a fresh-food counter that was distant from the main entrance/exit and also from the interior HVAC intake unit. The height of the dispersion was 2 m above the floor of the sales area. After ventilation of the interior space, the second scenario of the dispersion was started.

Scenario 2 involved spraying amyl acetate into the one of two rooftop HVAC units that was furthest from the entrance/exit. The anemostats were placed approximately 4 m above the floor of the sales area. The scheme demonstrating the interior space of the building, the HVAC system and the places of the dispersion during each scenario is given in Figure 1.

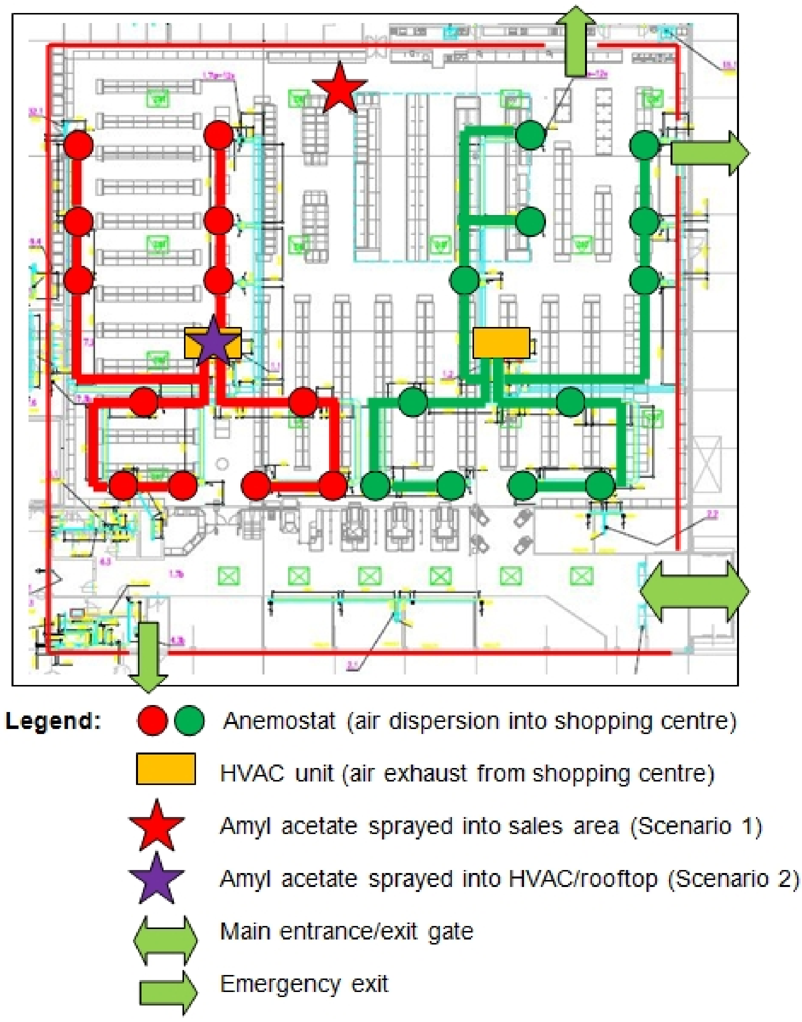

Figure 1: Plan of Shopping Centre with the HVAC System and the Locations of Amyl Acetate Dispersion

3. Results and Discussion

3.1. Experimental Dispersion of Amyl Acetate

Amyl acetate was sprayed into the sales area of a shopping centre by two methods. Analysis of the measured concentrations of amyl acetate confirmed that the spread of the substance is directly dependent on the elements of the HVAC system. A bar chart/scheme of sales area 5 minutes after dispersion of amyl acetate is shown in Figure 2 for Scenario 1, and in Figure 3 for Scenario 2.

By comparison of the measured data from both experiments, the assumption that the most dangerous scenario is the dispersion of a toxic substance from the exterior (Scenario 2) was confirmed. Amyl acetate spread into the interior of the sales area faster and contaminated the space more equally. During the dispersion of the substance into an exterior HVAC intake unit, we found that the rooftops, which are to ensure safety of microclimatic conditions in a building, paradoxically help the attackers to contaminate the whole interior of the shopping centre.

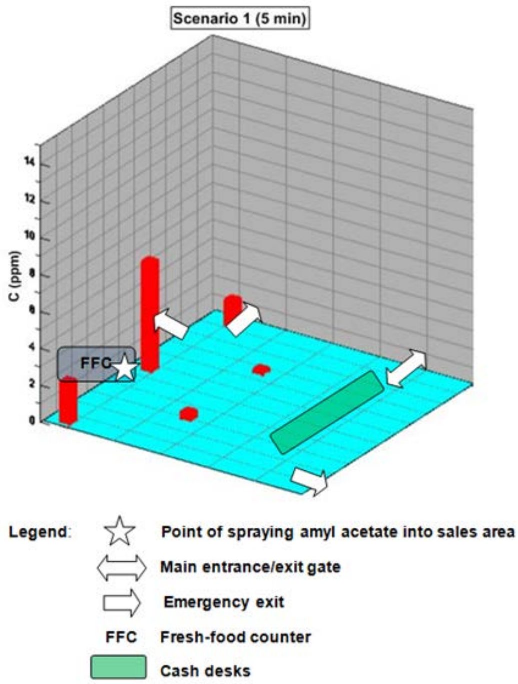

Figure 2: Bar Chart/Scheme of Sales Area 5 Minutes after Dispersion of Amyl Acetate (Scenario 1)

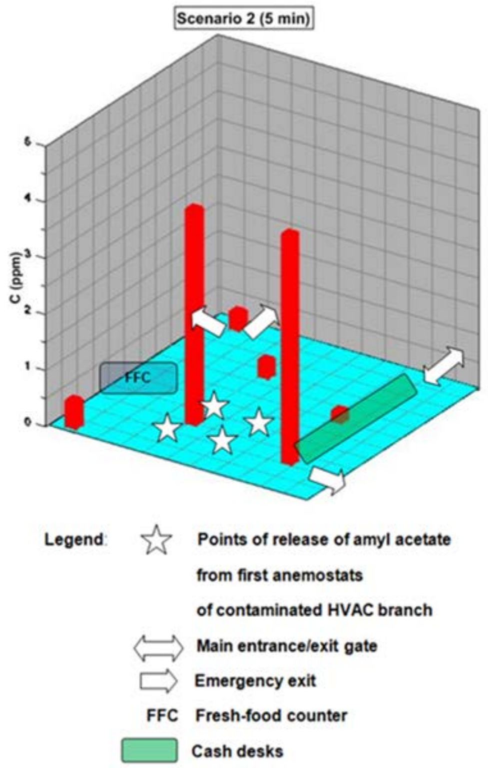

Figure 3: Bar Chart/Scheme of Sales Area 5 Minutes after Dispersion of Amyl Acetate (Scenario 2)

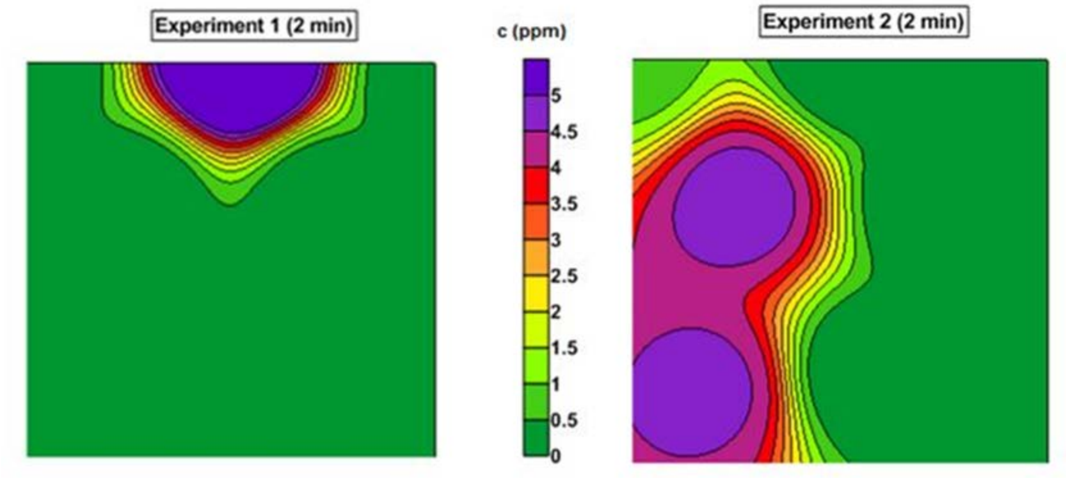

Figure 4: Dispersion of Amyl Acetate in the Sales Area 2 Minutes after Release within Scenario 1 (Left) and Scenario 2 (Right)

If the attackers used the intake of the rooftop unit as a single source of dispersion, the HVAC system would ensure further spreading of the substance. The toxic substance would spread by all the anemostats arranged in the system of the contaminated HVAC branch. This is backed up by Figure 4, in which the spread of amyl acetate in the sales area 2 minutes after the dispersion in both scenarios is compared.

During each experiment, 200 mL of amyl acetate was used. One could ask whether this amount of amyl acetate is sufficient, as the terrorists would likely use as much of a dangerous substance as possible to incapacitate individuals. A similar experiment was carried out in the auditorium of Technical University of Ostrava, The Czech Republic, also under a real air-conditioning scenario [6]. In this case, 1 L of amyl acetate was used, and the measured concentrations increased to over 30 ppm. For the purposes of determining the direction of the substance propagation in a sales area, the dispersed amount was appropriate because measured data were sufficient for the demonstration of the spread of a substance in the area and confirmed initial considerations on the essential role of the air-conditioning system. The fact that the HVAC system considerably influences the propagation of a substance in the area was shown by the conclusions of the experiment in the auditorium of Technical University of Ostrava [6]. The scheme of sales area/contour map illustrating the locations of amyl acetate dispersion is displayed as a contour map in Figure 5.

The propagation of substances is not only influenced by HVAC systems but also by the temperature and humidity. In the case whereby the microclimatic conditions are stable and in a declared range, the propagation of a substance in the area will also be stable. If the ventilation in a building is turned off, the microclimatic conditions will also change. With increasing temperature, the propagation of amyl acetate will accelerate and, with decreasing temperature, the propagation will slow down. The humidity has the opposite effect on the propagation of sarin in the space than it is with the temperature. The fastest propagation of sarin is likely to be during summer when the temperature in a building is set to 25ºC (in winter, the temperature may only be set to 18ºC) and the humidity of the environment is lower in summer than in winter.

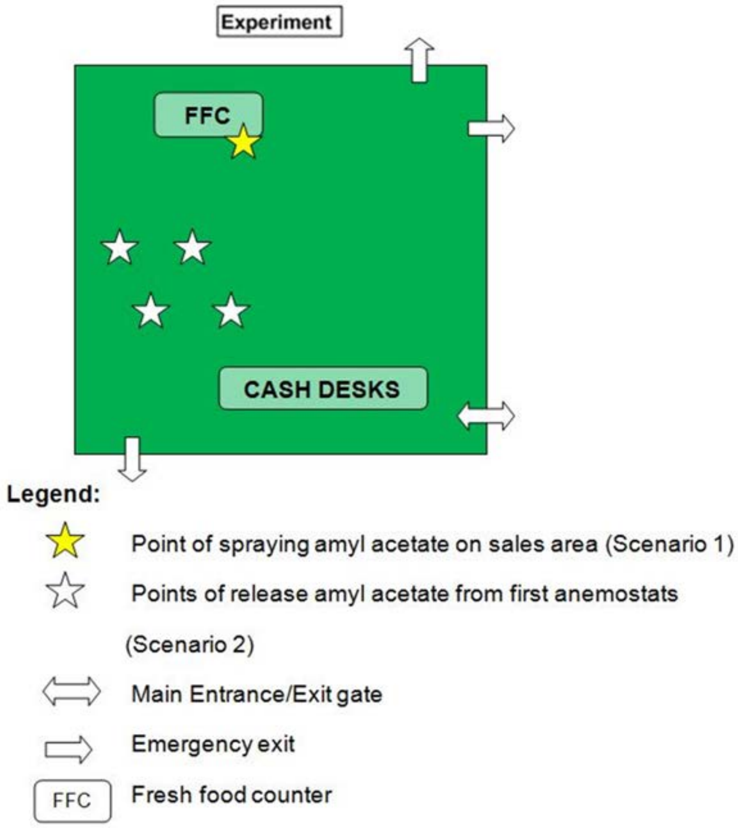

Figure 5: Contour Map/Scheme of Sales Area Illustrating the Locations of Amyl Acetate Dispersion.

3.2. Influence of the HVAC System on the Spread of Amyl Acetate

The primary factor influencing the direction and spread of the substance in the sales area was the HVAC system, which also includes entrances/exits and emergency exits of a building. During both experiments, we found that any change in the functionality of the above-mentioned HVAC elements caused a change in the dispersion of amyl acetate. The analysis of the data in various places of the sales area showed the following essential attributes that must be kept in mind to enhance the safety of a shopping centre:

The HVAC exhaust intake unit must be placed above the site with the highest number of customers. In the case of the studied building, neither the place with the fresh-food counter (cheese, sausages) nor the cash-desk area was fitted with an exhaust intake unit. In the case of dispersion of a dangerous substance due to the anemostats, the visitors in these places would not be sufficiently protected.

The HVAC exhaust intake unit must be installed at the same place as the first anemostats of each HVAC branch. During the dispersion of the substance from the exterior rooftop unit, the anemostats are the nearest diffusers that participate in the widespread penetration into the shopping centre. Therefore, it is essential to allow accelerated exhaust of the released substances in this location.

The HVAC rooftop units must be ensured against misuse. The security of rooftops should be ensured in all commercial chains. HVAC equipment should be ensured straight on the roof of a building and inside the building as well. In the case of discovery of health problems of a large number of people, it is necessary to find out the source of the leak of a dangerous substance. The essential information for the estimation of the substance direction of dispersion is whether the substance is released directly into the area or spreads via the anemostats. Therefore, it would be appropriate to prevent the rooftops against misuse and also to ensure rooftop monitoring via a CCTV (closed-circuit television) monitoring system.

HVAC elements have to be installed in all corners of a major sales space. The substance dispersed in an air-conditioned interior is carried away by the flowing air. As long as the corners of a room are without any exhaust system, the contaminant will accumulate there. Furthermore, amyl acetate is capable of adhering to the walls of a room, which contributes to an increase in its concentration in this location. The installation of emergency exits or exhaust HVAC units would solve this problem.

Toxic substances have to be ventilated from the sales area onto the roof of a building via the HVAC units. The measured concentrations of amyl acetate were very low below the HVAC rooftop units during both experiments, and so, when the dangerous substance was ventilated onto the roof, there was a low risk of contamination of the building's surroundings. Despite this fact, in the case of a prospective evacuation, it is necessary to observe the principle that the evacuation assembly should be facing away from the wind where there is not a high risk of the substance spreading from the roof.

Ensuring higher performance of the HVAC system to allow ventilation of a dangerous substance out of a building. If the presence of a dangerous chemical is detected in the sales area, it is necessary to ensure that it can be immediately exhausted onto the roof of a building.

The principle that the HVAC system is the most significant factor influencing the spread of a toxic substance was also confirmed in the study of the experts from Lawrence Berkeley National Laboratory (USA) [7]. The study [7] analyses situations in which terrorists disperse a toxic substance through the HVAC system inside a building. This incident is addressed here from the viewpoint of the HVAC system, and their conclusions are in accordance with our findings. The authors of the study [7] considered an intentional terrorist attack with the aim of killing civilians by means of applying a large amount of a toxic substance. As a countermeasure, they recommended using the HVAC system to force as much outside air as possible into the contaminated area and, in this way, diluting the concentration of a toxic substance inside the building. In their study, they rejected the recommendation of the specialists from the Protective Design Centre (USA) [8], who, as the primary countermeasure, suggested that the building should be closed and the situation should be resolved after the identification and quantification of a toxic substance. The authors of the study [7] also highlighted the fact that the exhaustion of a toxic substance out of a building must be very effective since most chemicals are much heavier than air and tend to accumulate on the ground layer on the floor. In a shopping centre, this also means that ventilation out of a building from among the racks and under the shelves will be difficult. The task of bringing outside air into a building and taking the contaminated air out of a building will be up to the operators of the HVAC system. The operating personnel must be sure which exterior HVAC intake unit was contaminated so that it is not be activated to the highest performance by mistake, because, in this way, even more contaminated air would be carried into the interior. Therefore, it is necessary to ensure monitoring of the roof of a building by CCTV cameras. Contaminated air from the building will be taken away through the rooftop units to the roof and will spread further into the clear surroundings, which may result in the contamination of the outside atmosphere. Releasing a toxic substance is not supposed to be too risky for individuals in the vicinity, as was described by John Seinfeld in his publication called Atmospheric Chemistry and Physics of Air Pollution [9]. The author addressed a one-time leak of gas into the atmosphere, called an airborne plume, from a 2-m gap at a wind speed of 3 m/s on a flat surface. After 100 m, the releasing gas is dispersed into a cloud (size 20 x 10 m), which means that the diluting factor of a released substance has, after 100 m, a value of 50. If this calculation is made with a higher wind-speed value, the diluting factor at a distance of 100 m from the release can achieve the value of even several hundred. This means that the toxic substance released from the rooftops should not threaten individuals near a building.

4. Conclusion

Determination of the direction and speed of propagation of a chemical compound revealed weaknesses in the protection of a public building equipped with a HVAC system. In the case of a chemical attack, security of an air-conditioned building, specifically a shopping centre, is primarily dependent on the location of HVAC elements and the initial reaction of the employees.

Experimental measurements were performed in two scenarios in which 200 mL of amyl acetate was dispersed with nitrogen as the carrier gas. The first scenario was made in the interior of the building at a location where the highest concentration of people was expected. A significant impact of HVAC elements on the spread of amyl acetate was confirmed. In this scenario, the sprayed chemical substance accumulated in those places that do not have any HVAC elements. A high concentration of amyl acetate in these places is one weakness in building security.

The second scenario was carried out by spraying amyl acetate directly into the intake rooftop of the HVAC unit. In this case, amyl acetate was immediately dispersed into the HVAC branch and consequently to ventilation fans, the so-called anemostats. From a height of 4 m, amyl acetate started to disperse into the interior of the building within 1 minute after being sprayed. As the highest risk scenario was evaluated as being during this second experiment, the ventilation fans served as auxiliary devices for dispersion of hazardous substance throughout the facility.

From processed study results following recommendations for security management of shopping centre. The primary activity that must be performed by operational staff when detecting dangerous substances in the building is to exhaust the chemical substance from the interior to the roof of the building and to evacuate people from the building as soon as possible. To ensure proper ventilation and direction of evacuation, it is necessary to find out the location of the chemical release. For this reason, using the monitoring system is a crucial requirement of building security.

The results from the experimental data are valid for any substance that has physical properties similar to amyl acetate or sarin. Generalization is valid for substances heavier than the air, i.e. they spread along the ground, cause death through inhalation intoxication and are released in the form of an aerosol applied via pressure diffusion. Determination of the direction and the speed of the propagation of a dispersed substance revealed the weaknesses in the protection of a population in a building that is primarily dependent on the placement of HVAC elements, reactions of the management and other aspects. In this article, we suggest that better distribution of elements of the HVAC system could eliminate the negative impact of a toxic substance on the health of people visiting the building.

Acknowledgements

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