Analysis of Ventilation Efficiency in the Earth Covered Magazine for Ammunition Storage Using Numerical Simulation

Nurin Zecevic 1, Jasmin Terzic 1, Berko Zecevic 1, Adis Ajanovic 1

1 Mechanical Engineering Faculty, University of Sarajevo, Vilsonovo setalise 9, Sarajevo, Bosnia and Herzegovina
zecevicn@mef.unsa.ba

Abstract. Internal environment parameters such as temperature, relative humidity and airflow velocity in ammunition storage facilities have a significant impact on the condition and overall life of ammunition, especially on the process of ammunition degradation in situations when their values deviate from required standards for safe storage. High temperatures inside the magazine, as well as in the ammunition packaging, can have a very negative effect on the structure of ammunition and explosives, and high values of relative humidity can result in corrosion and rapid decomposition of chemical compounds. Therefore, a properly designed ventilation system should ensure that the values of internal temperature and relative humidity are within the permitted limits, which is a very important aspect of the storage process itself, so that ammunition and explosives can be completely safe and ready for transport, use and handling.

Experimental studies conducted in several magazines of ammunition and explosives in Bosnia and Herzegovina (BiH), had aim to monitor changes of environmental parameters such as temperature, relative humidity and airflow velocity. During these experimental measurements, high values of relative humidity were in these magazines observed, as well as uneven airflow in some ventilation ducts. The main cause of such measured values can be related to the inadequate performance of the natural ventilation system of the analysed magazines. Using numerical simulations (finite volume method) in the ANSYS – Fluent program, the analysis of the existing ventilation system of earth covered magazine in BiH from the aspect of airflow velocity was performed, as well as analysis of modifications that can improve airflow within the analysed magazine. The results of numerical simulation for the existing state of analysed magazine corresponded to the results of airflow measurements at certain places in the magazine. It was confirmed that the existing ventilation system does not provide proper ventilation, which further causes higher relative humidity values. The results of numerical simulation for the proposed modifications of the ventilation system have shown significantly better air circulation in the magazine, i.e. that a more efficient natural ventilation was achieved.

1. Introduction
Influence of natural environment on ammunition and weapon performance are the subject of continuous study, with the aim to estimate shelf life of ammunition, and establish supervision and control of ammunition quality from the aspect of storage, transport and use. Although a lot of attention is being paid to the problem of ammunition storage and analysis of the factors that affecting the life cycle of ammunition, satisfactory results have not yet been achieved in the assessment of life cycle. Lifetime of ammunition is very often limited with propellant aging and condition of storage ammunition [1, 12].
Good storage, handling and the use of ammunition require that ammunition should be kept dry and well ventilated, kept as cool as possible and free from excessive or frequent changes of temperature, protected from the direct rays of the sun and handled with care [2, 3]. Otherwise, it may deteriorate or become damaged if it is not correctly stored, handled and transported, consequently it cannot function as designed and become dangerous for use [1, 12].

The environmental requirements (temperature, humidity and vibration) of ammunition and explosives (AE) vary and are dependent on their intended storage conditions, transportation, handling and use [1]. The temperature in the storage should be generally maintained between 5 and 25 °C [4]. In the situation of storing AE for a longer period, it is necessary to take into account that the temperature values are not the same during the summer and winter period, and there are differences in daily values. Temperature values, lower and higher than the standard, can have a very negative effect on the structure and performance of AE in the storage. Very low temperatures are not as objectionable as high ones, but explosives that contain Nitroglycerine can become dangerous at very low temperature or it can change physical properties of material of which explosive is composed [1, 2, 12]. Effects of high temperatures can be physical, chemical effects or combined influence of these two effects. It is important to emphasis that during high temperature and high humidity, negative effects are more significant than when it is lower temperature. Higher air temperature can intensify degradation reaction of certain components inside of explosive matters and reduce ballistic performance or cause chemical degradation of material and appearance of gases that can cause cracks in the propellant. Increasing temperature inside of warehouse for 10 °C will generally accelerate chemical reactions for 2 to 3 times. Materials such as rubber and various type of plastic rapidly age with the increasing of ambient temperature, especially if they are to the direct sun and ultraviolet radiation exposed. Those materials become hard and brittle, and rough handling or ignition can cause failure of this subsystem [1, 12].

Impact of humidity in the storage can be very complex and significantly depends on air temperature. During ammunition storage, temperature fluctuations are very dangerous during daily cycle with the presence of high humidity, which can cause rapid aging of energetic material. The relative humidity should be between 50-60% maintained, when steel objects can be stored without any problem. When relative humidity is above 60 %, the process of corrosion begins on metal objects and if water vapor is present in the air, then the corrosion process is intense. Higher relative humidity can cause ammunition damage, and lower humidity can cause static electricity for some type of stock [4]. Direct contact of moisture with metal surfaces that are not enough surface protected causes corrosion and increases explosive material degradation and reaction with the remains of acid. It can also influence on ammunition components and cause uncontrolled chemical reactions, very often with unwanted consequences - when moisture migrates in the chain combustion system, it can lead to the failure of overall system in the phase of launching [1, 12].

The performance of explosives will be unpredictable and the safety will be reduced if the manufacturers’ environmental conditions are not met [5]. To optimise the life of stored explosives, and protect it from moisture and excessive changes in temperature, it is desirable to regularly control and maintain temperature at reasonable level and provide adequate ventilation. The issue of ammunition maintenance is crucial and every effort should be made to ensure dry conditions prevail in storage and transportation, because rain, dampness and humidity can cause enormous damage to ammunition and explosive in a very short time [3, 6].

2. Case study – Measurement of environmental parameters in AE storage
There are significant number of AE storage sites in BiH, where two characteristic types of storage predominate, Above Ground Magazines (AGM) and Earth Covered Magazines (ECM). Worldwide, ECMs are mainly primary choice for storage of AE in terms of safety and economic. These storages are characteristic by its structure and earth cover layer over the top, side and rear of ECM [7]. However,
many ECM interiors have serious moisture-intrusion problems, due to the water seepage or inflow through concrete walls, floors, ceiling joint and door seals. In addition, to facilitating more water intrusion, concrete damage will progress over time until affected ECMs are unsafe to use, adding to the Army’s increasing maintenance, repair and replacement burdens [8]. Today, many advanced military structures are making great efforts and financial investments to build new improved military objects for AE storages. On the other side, countries that are not able to provide such demand investments turn to improvements of existing storage locations, as it is the case in BiH.

ECMs that are in BiH found, are standard warehouses marked as “U”, and the most common types are U-15 and U-20. According to the NATO and USA standard, they are considered as undefined ECMs, and as such provide the lowest level of blast resistance and require the greatest separation distances between warehouses [7]. In 2014, experimental study that was conducted in several AE storages at different geographical and climatic locations in BiH, had an aim to identify and monitor changes of environmental parameters such as temperature, relative humidity and airflow velocity in these storages. These parameters were measured in every storage with sensors resistant to external conditions and characterized as safe to work with in AE storage [12]. Although measurements included AGMs and ECMs, measurement results are shown in this paper only for ECM storage.

Analysed ammunition storage ECM U-15 is located along a valley surrounded by mountains and along the creek, running through valley. It is consisted of semicircular reinforced concrete arch with radius 5.4 m, reinforced headwall with two reinforced concrete wings. Sidewalls, inside, are made of plain reinforced concrete panels. The entrance door is metal, consisted of steel frame, sheet steel cladding with thermal insulation filling. Windows are fixed, metal with steel bars from the outside. Inside dimensions of the magazine are 11.00 x 14.70 m [1, 12]. Layout of ECM with pallets is shown on figure 1.

Figure 1. Layout of the ECM U-15 [12].

Magazine does not have HVAC system. Ventilation is natural, with two inlets for fresh air supply, ventilation ducts for airflow along side (horizontal ducts) and back wall of the storage. In the middle of the back wall, a vertical ventilation duct drains air through the outlet to the outside of soil-covered layer. All openings have ventilation grilles and have nets to prevent rodents from entering, but do not prevent entry of insects. Inside of the magazine, in the lower part of side walls, there are 10 ventilation openings,
dimensions 400x400 mm, and 2 ventilation openings at the top of back wall [1, 12]. Sections of the ECM are shown on figure 2.

![Figure 2. Longitudinal (left) section and cross section (right) of the ECM back wall [12].](image)

Measurements showed that generally during most of the time of a year, relative humidity on ECM location was in the range 60-95 % and maximum environmental temperature did not across 35 °C. Temperature inside of the magazine during considered period was in the range from 5°C to 18°C, which is suitable for a long-term ammunition storage, because there are no conditions that can trigger the accelerated degradation of weak explosives (propellant charge, black powder and pyrotechnics). Average relative humidity inside of the ECM was 50% to 95% with very large amplitudes of relative humidity change within a short measurement period, which clearly points to the problem with natural ventilation system of the magazine [1, 12].

Due to the measured extremely high humidity values in analysed magazine, additional measurement of temperature and relative humidity was conducted in ammunition wooden boxes. Temperature values inside of these boxes were higher than temperature amplitudes in the magazine. Relative humidity in the wooden box was in the range 60-90%. This high relative humidity inside of wooden boxes represents a great danger for intensifying corrosion process of metal ammunition surfaces, and especially if there is possibility for negative impact on pyrotechnic elements (traces, fuse, ignition charge etc) and on electronic components like guided ammunitions [1, 12].

As part of the research was also the measurement of airflow velocity through the entrance of ventilation ducts and on the main exhaust duct, inside and outside of the magazine [12]. Measurement points in the magazine are shown on figures 1 and 2, and results are shown in table 1. Measurements on characteristic points showed large differences in the values of airflow velocities. On some measurement places as M4 and M12, airflow velocity was 0 m/s, which indicates there is no air circulation at all. On measurement places M3 and M14, partitions for closing the inner side of air inlet duct were noticed, which should be not allowed because it restrics inflow of fresh air in the magazine. Right inlet of the ventilation duct (M2) at the headwall of the magazine had upside down sliding valves for opening and closing of the duct, which also led to much lower air flow in comparance with M1 inlet duct.

Since natural ventilation depends on natural factors with variable intensity and different durations (different temperature differences, intensity and direction of the wind), it is not constantly uniform and occasionally not even effective enough. Natural ventilation in magazines without openable windows means exchange of air through ducts (horizontal canals) and through vertical ventilation duct that extends from magazine to above the covering earth layer of the magazine. It is important that this type of natural ventilation system with ventilation ducts will work properly only if a constant supply of fresh air in appropriate quantities is ensured [9].
Table 1. Results of airflow velocity measurement in ECM [12].

| Measurement place | Velocity, m/s | Measurement place | Velocity, m/s |
|-------------------|---------------|-------------------|---------------|
| M1                | 1.65          | M10               | 0.25          |
| M2                | 0.32          | M11               | 0.18          |
| M3                | 0.00          | M12               | 0.00          |
| M4                | 0.17          | M13               | 0.14          |
| M5                | 0.00          | M14               | Closed vent   |
| M6                | 0.25          | M15               | 0.15          |
| M7                | 0.25          | M16               | 0.42          |
| M8                | 0.05          | M17               | 1.22          |
| M9                | 0.14          | M18               | 1.40          |

3. Assessment of ventilation efficiency in ECM using numerical simulation

Considering that, the results of the study showed that there was not enough or no air exchange at all in some ventilation openings (Table 1), in the following chapters, it will be assessed and considered with which measures it is possible to improve the airflow of selected ECM, through achievement of optimal number of air changes within the magazine. The research is performed using a numerical simulation. Initially, the simulation of airflow in the analyzed magazine U15 was performed based on the existing state and known parameters. Through numerical simulation of airflow in the magazine with certain changes, structural and mechanical, it was estimated whether these changes would contribute to more efficient ventilation of ECM U-15.

Three cases are considered. First case is a numerical simulation of airflow in analyzed ECM, based on its current state and known parameters (Figure 1).

In order to improve the airflow in the magazine, two modifications are considered:

- Modification 1. In this case, changes are implemented in the natural ventilation system, in such a way, that the inlet openings are directly connected to the side channels, which is not the case with the current state of the magazine, and existing inlet openings on the inside of the magazine are closed (Figure 3). Number of openings on the ventilation chimney was increased because existing ventilation chimney has only two outlet openings. With direct connection of inlet and sidewall channels, air velocity will increase and thus it is expected that the air from the magazine will now go smoothly through sidewall openings and channels.

- Modification 2. Replacing existing door with a new exterior door according to the NATO specifications, with two additional ventilation openings on the magazine door (in accordance with U.S.A. magazine solutions). Dimensions of the air inlet openings on the underside are 850x150 mm and the bevel angle is 45°. Existing inlet openings on the headwall of magazine will be closed. On the ventilation chimney, number of openings will be increased, on all four sides for air outlet.
Figure 3. Schematic view of inlet openings on the magazine headwall: existing state (left) and Modification 1 (middle); Modification 2. A view of front door with built-in ventilation openings (right).

3.1. Computational Method
Numerical simulation of flow field inside of the magazine is obtained with the computational fluid dynamics software ANSYS Fluent. For all simulations, following conditions are adopted:

- Working fluid is air, an ideal gas, which is modified according to compressibility and changes in thermophysical characteristics with temperature. Density and viscosity depend on temperature, and conductivity are considered as constant.
- Parameters of free airflow correspond to parameters of the air at altitude of considered magazine location according to standard ICAO atmosphere.
- The flow is turbulent and for simulation of turbulent flows in magazine is used Spalart-Almaras model (SA) [10].
- Discretization of spatial domain is performed by a unstructured mesh.
- Numerical method „pressure-based solver“ is being used, which simultaneously solves the equations of continuity, momentum and energy.
- The equations are linearized in implicit form, i.e. for given variables, unknown values in each cells are calculated using relations that include both existing and unknown values from adjacent cells.

3.2. Model geometry
Using AutoCAD program, 3D model of the magazine is defined with stocks (full magazine) based on available drawings of the magazine, in scale 1:1. For the analysis of airflow in 3D model of the magazine, only the part where air can circulate was singled out (nets and flaps for closing all openings were neglected).

The mesh for the geometry was prepared using ANSYS® Meshing. Nielsen et all. in their book mentioned a formula (derived from the German guideline VDI 6019) that can be used as a rough guideline for the sufficient number of cells as $4.44 \times 10^3 V^{0.38}$, where $V$ is the room volume [11]. Using this formula for the simulated room gives the number of cells as about 483,525. However, this formula does not address the cell distribution and the quality of the cells. Generally, higher resolution is necessary in areas of relevant flow phenomena such as plumes above the heat source. The chosen meshing method for generating tetrahedral cells does take into account a greater number of cells at the inlet and outlet boundary interface, as well as in the chimney section (taking into account that Academic versions of Fluent are limited to 512K cells). Generally, in CFD studies, it is important to find a mesh-independent solution. It means that the solution does not change significantly if a mesh is further refined. A study to find a mesh-independent solution was not conducted here. Depending on the geometry of
considered three cases of the magazine in this paper, following number of cells are being used (figure 4): 456,574 cells (existing state), 509,242 cells (Modification 1) and 476,403 cells (Modification 2). Number of cells in all three cases is about the value obtained by the formula of Nielsen et all.

![Figure 4. Computational domain for existing state (left) and Modification 2 (right).](image)

Chosen are following types of boundary (figure 5): wall, pressure – inlet (blue arrows) and pressure – outlet (red arrows).

![Figure 5. Boundary conditions on inlet and outlet: Existing state (left), Modification 1 (middle) and Modification 2 (right).](image)

At wall boundary, chosen are options “stationary wall” and “no-slip”, because in the considered case the viscous effects cannot be ignored. The mass flux through the “wall” boundary is zero, and pressure values on this boundary are obtained by extrapolation from the inside of solution domain. Pressure – inlet boundary is set on the entrance of ventilation surfaces of the magazine and the initial conditions of airflow are: \( p_{in} = 93,006 \) Pa and \( T_{in} = 10.34 \) °C. Pressure – outlet boundary is set on ventilation chimney outlets with: pressure \( p_{out} = 93,003 \) Pa and temperature \( T_{out} = 10.29 \) °C.

4. Results and Discussion
The CFD simulations in this work were conducted using ANSYS® Fluent. After the mesh was imported to ANSYS® Fluent and after selecting the CFD models, the general solution methods were set. SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) scheme was selected for pressure-velocity coupling scheme in solution methods. Standards for pressure and second order upwind for momentum, turbulence equations and energy equations were set as the discretization schemes. The limits for residuals for all the equations was set as 1E-03 and for the energy equation as 1E-06. The under-relaxation factors were set to default.
For verification of numerical simulation with defined initial and boundary conditions, the first case of the magazine without any modifications was used. On the figure 6, it can be observed that air streams enter the object, go to the vents on the back wall and further to chimney. The speed of streams decreases significantly inside of the magazine due to the existing ammunition stocks. Very little air flows to the sidewall channels (flow speed is approximately 0.1 m/s), and slightly higher velocity of the flow is through the lower openings on the back wall to the back channel (about 0.2 m/s). At the outlet, speed is between 0.7 and 1.37 m/s from the center of the opening to the top of the outlet opening. Based on this, it indicates there is a good agreement between results of experimental measurements, and that the set numerical model can be used for analysis of the airflow for the case of proposed modifications.

**Figure 6.** Results of simulation for existing state: Velocity streamlines (left), velocity magnitude in three different cross-sections (right).

Results of numerical simulation for the case of Modification 1 of the ECM magazine (figure 7- left), shows that air streams now directly pass from inlet openings to the side channels, and exit through side openings in the space intended for storage of ammunition and explosives. The airflow velocity on the exit of ventilation chimney is significantly much larger. Air circulation in the magazine is asymmetrical, it is better in the part of the magazine where there are more ammunition stocks.

**Figure 7.** Results of simulation for Modification 1: Velocity streamlines (left), velocity magnitude in two different cross-sections (right).

In the case of numerical simulation for Modification 2 (new entrance door with two build-in vents), a more intense airflow into the magazine is observed, as it can be seen on Figure 8. Since fresh air enters through vents on the magazine door, air streams go smoothly towards the ceiling and further to the back part of the magazine, where part of the streams bounce off the wall and return to the door. Part of the streams goes around the stockpiles of AE on both sides of the magazine, and through openings of the sidewall channels. Comparing the results of airflow simulation of second modification with results of airflow simulation of the first modification, it shows that in the second modification are achieved more efficient airflow in the magazine and with replacement of the entrance door, the safety aspect of the object was improved.
Figure 8 (left) shows that there is very little airflow towards the side channels (flow velocities are less than 0.1 m/s). The airflow velocity, through lower openings towards the back channel is about 0.2 m/s, and at the outlet openings, the velocity is between 0.45 m/s to 0.93 m/s from the center to the top of outlet opening.

**Figure 8.** Results of simulation for Modification 2: Velocity streamlines (left), velocity magnitude in three different cross-sections (right).

Figures 9 and 10 show differences in the velocities of certain layers of the air in the magazine for current state and with suggested modifications. In the case of a numerical simulation of the current state of ECM, it is clear that large amount of the air remains in the magazine. In the case of first modification, results are not in accordance with expected improvement. Air is more concentrated in the sidewall channels and there is a poor air circulation in the magazine, i.e. more saturated air remains in the space for AE storage. In this case, more air significantly remains than in the existing state. Second modification provided the most favourable circulation of the air (airflow velocities are higher than 0.2 m/s) in the magazine, ensuring the replacement of the existing saturated air and reducing the level of relative humidity.

**Figure 9.** Isosurface with v>0.1 m/s for all three-simulation cases: Existing state (left), Modification 1 (middle), Modification 2 (right).

**Figure 10.** Isosurface with v>0.2 m/s for all three-simulation cases: Existing state (left), Modification 1 (middle), Modification 2 (right).

5. **Conclusion**

The aim of the paper was the analysis of ventilation system efficiency in magazine for ammunition storage. The basis for analysis are studies that have shown that certain environmental parameters can significantly affect the stability and safety of AE storage, if their values deviate from recommended
ones. Magazine ECM U-15 in Bosnia and Herzegovina is the subject of analysis, in which, according to the implemented experimental study, were measured higher values of relative humidity, indicating the inefficient operation of natural ventilation system of the magazine.

In this paper, certain numerical simulations were performed, using ANSYS Fluent program for the analysis of the airflow for the existing state of the magazine and two modifications, including mechanical and structural measures. Results of numerical simulation for existing state of analyzed magazine showed very good agreement with the results of measurement of airflow velocity at certain points in the object, confirming that the existing ventilation system does not provide proper ventilation. Although it was firstly assumed that with Modification 1 magazine would have a better air circulation, numerical simulation showed that although the inlet and side channels were directly connected as opposed to the current situation, more efficient ventilation system was not achieved. The analysis of the results of numerical simulation for the case of Modification 2 (installation of new door with two built-in vents, according to the NATO specifications), showed significantly better air circulation inside the magazine, i.e. optimal air exchange was achieved through a better natural ventilation system. For further analysis of airflow in the magazine, a more details should be taken into account, considering other factors that have influence on natural ventilation flow, such as size and position of built-in ventilation openings on the door, grids on all inlet openings, environmental conditions, location and size of the magazine.

References
[1] B. Zecevic, N. Zecevic, J. Terzic and M. Sain, “Researching influence of climatic environmental parameters on performance of large calibre ammunition during storage”, 2015 1st International Conference on Environmental Science and Technology, pp. 63-73, 2015.
[2] Government of Sweden, “Best Practice Guide on Physical Security of Stockpiles of Conventional Ammunition”, FSC.DEL/56/08/Rev.2, 2008.
[3] SEESAC, “Ammunition and Explosive Storage and Safety”, RMDS/G 05.40, 4th Edition, UNDP Belgrade, Serbia, 2006.
[4] Ministry of Defence and Defence Safety Authority, “Defence Code of Practice (DCOP) and Guidance Notes for In-Service and Operational Safety Management of OME”, DSA 03.OME Part 2 (JSP 482), Defence OME Safety Regulator, 2019.
[5] GICHD, “A Guide to Ammunition Storage”, First Edition, Geneva, ISBN 940369-15-1, 2008.
[6] Department of the Army, “Army and Explosives Safety Standards”, Department of the Army Pamphlet 385-64, Washington DC, 2011.
[7] Website: https://www.wbdg.org/building-types/ammunition-explosive-magazines
[8] M. K. McInerney, S. M. Jr. Orange and A. G. Lawrance, “Demonstration of Dehumidification for Corrosion Control in Earth Covered Magazine”, DoD Corrosion Prevention and Control Program, Construction Engineering and Research Laboratory ERDC/CERL TR-18-34, 2018.
[9] M. Zagorec and P. Donjerković, “Analysis of natural ventilation in buildings”, Građevinar 58, Vol 5, pp. 385-393, 2006.
[10] M. Barbason, and S. Reiter, “About the choice of a turbulence model in building physics Simulations”, Proceedings of the 7th conference on Indoor Air Quality, Ventilation and Energy Conservation in buildings, 2010.
[11] S. Shah, and K. Dufva, “CFD modeling of airflow in a kitchen environment : Towards improving energy efficiency in buildings”, South-Eastern Finland University of Applied Sciences, 2017.
[12] B. Zecevic, N. Zecevic, J. Terzic and M. Sain: Monitoring changes of temperature and humidity in ammunition storages under the Armed Forces of Bosnia and Herzegovina, UNDP in Bosnia and Herzegovina, Sarajevo, 2015.