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2D MODELING AND NUMERICAL SIMULATION BY ANSYS CFD OF THE PISTON EFFECT IN SUBWAY STATION

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This paper presents the carrying out of a study on the circulation of air currents inside galleries and subway stations. The purpose of this case study is to determine which are the best methods for the controlling and directing the air current generated by subway trains through the piston effect. This article presents the results obtained by modeling and CFD numerical simulation, with the help of ANSYS program, of two cases. The first case in which the buffer chamber is normal and the second case in which the geometry of the buffer chamber was modified by adding an air intake angled to 45 degrees. The results of the CFD modelling and simulations in this paper show that the air piston can be redirected before it reaches the metro station, thus increasing the comfort of the passengers in the subway stations.

Keywords: subway, piston effect, air piston, baffle chamber, computational fluid dynamics

1. Introduction

Bucharest is one of the great European capitals which benefits from a subway network built nearly 40 years ago. Construction works for the Bucharest subway began in 1977 together with the founding of Bucharest Subway Enterprise. The design and actual construction of the first subway trains started after this date [1, 2, 3]. Currently, over 750000 travellers benefit daily from the underground transportation [4]. However, passengers need to be ensured a favourable micro-climate which entails a certain degree of comfort but also a high air quality.

The air quality inside the subway is directly affected by the environment, with a close relationship between the inner air and the outside air [5, 6, 7, 8, 9]. External pollutants are aspirated by the ventilation systems of the subway, but also by the air piston created by the train movement on the tunnel influencing the air quality in the subway [10].

Air currents play an important role in substance and temperature exchanges in the subway [11]. The balance between an air current that is too high and an

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insufficient one is hard to attain in the current conditions of the subway due to the limited options of underground construction.

Chinese researcher Yang analysed the role of the piston effect regarding the degree of passenger comfort simulating the distribution of the air movement for the trains entering and exiting the station. In line with the studies carried out by Yang, the instantaneous speed of the air current on the platform and at the level of the lobby must not be higher than 5 m/s [12].

In Romania, studies on the influence of the air piston on the quality and comfort of the passengers in the subway are poorly represented. The air piston creates discomfort for the subway travellers due to the variations of air pressure, speed and temperature. The control and redirecting of the air piston created by the movement of the trains through subways galleries can lead to an increase in the degree of comfort for the passengers in subway stations.

The main concern of this study was to numerically simulate the air piston generated by the subway train movement in the tunnel on its entrance into the station through the buffer chamber, as well as to test the hypothesis in line with which through the introduction of an air intake before the station, one can achieve the deviation of the air piston.

One can notice that a 2D simulation is inferior to a 3D simulation, due to the low precision of the results in comparison to the 3D simulation. Regardless of these shortcomings, 2D simulation is less expensive, generates rapid results, with sufficiently good results, for the studying of a phenomenon on a general level. Based on the general information, one can decide, whether it is useful to go to a three-dimensional modeling and simulation. In comparison with 2D simulations, 3D simulations are expensive and take longer until the generation of results.

2. The studied cases - Working methodology

In this paper two two-dimensional modeling and CFD simulations of two cases are presented:

- Case 1 – NBC (normal buffer chamber). In this case a model of a subway station consisting of: a tunnel, normal buffer chamber and passenger station is presented (Fig. 1);

- Case 2 – MBC (modified buffer chamber). In this case the model of the subway station was modified through the introduction into the geometry of the buffer chamber, of an air intake angled to 45 degree (Fig. 2). The air intakes communicates directly to the outside being taken into account as an exit in the Fluent setting.

The CFD analysis of program Fluent was chosen for the carrying out of the numerical simulation of the air current speed generated by the piston effect in one of the subway stations in Bucharest. In the CFD simulation, the air speed is considered to be constant of 16.6 m/s. For the execution of the 2D geometry DesignModeler application was used and the integration network was executed in Workbench 19.2 platform. Workbench program joins in one interface all the tools of the ANSYS soft [13].

For the execution of this computer analysis, a physical model of a subway station in Bucharest was commenced. The Physical model of the system NBC consisting in a portion of the tunnel, the buffer chamber and a platform station, all interconnected with each other (Fig. 1) was executed in line with the measurements carried out "in situ" so that the 2D model would better reflect reality.

The characteristics of the building elements used in the CFD modeling and simulation.

Case 1 NBC:

- Tunnel diameter D_T = 5.6 m;
- Tunnel length L_T = 200 m;
- Buffer chamber length L_{BF} = 6 m;
- Buffer chamber height H_{BF} = 6 m;
- Station platform length L_S = 50 m;
- Station height H_S = 6 m.

Case 2 MBC - the buffer chamber was modified by adding an air intake with the following sizes: L_1 = 23 m, L_2 = 15 m, L_3 = 5 m, and height Hs = 14 m.

The 2D geometry was executed in DesignModeler Workbench program taking into account the sizes of the building elements resulting after the measurements in the subway stations.

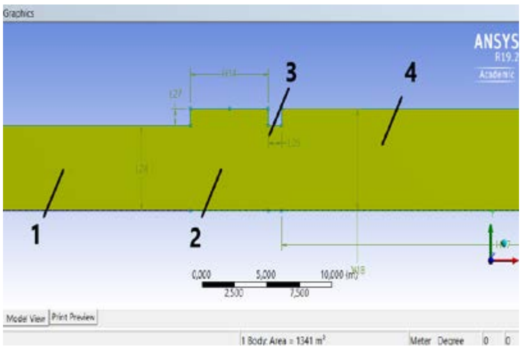

Fig. 1. Subway station geometry - NBC case

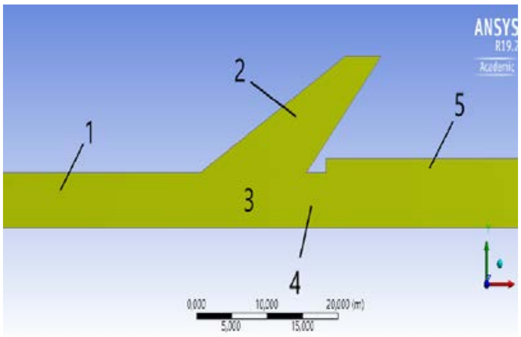

Fig. 2. Subway station geometry - MBC case

In Figure 1 the geometry elements of the NBC case are presented: 1) tunnel, 2) buffer chamber, 3) diaphragm, 4) station platform. In Figure 2 the geometry elements of the MBC case are presented: 1) tunnel, 2) inclined air outlet at 45 degrees, 3) buffer chamber, 4) diaphragm, 5) station platform.

Table 1

Characteristics of the integration network for case NBC and MBC

	Type	Case NBC	Case MBC
Object Names	*Mesh*	✓	✓
Physics Preference	*CFD*	✓	✓
Solver Preference	*Fluent*	✓	✓
Sizing	*Growth Rate* - Default	1.2	1.2
	Defeature Size - Default	6.4268e-002 m	6.4268e-002 m
	Curvature Min Size	0.12854 m	0.12854 m
	Average Surface Area	1341 m^2	1458.2 m^2
Quality	*Target Skewness*	0.900000	0.900000
Statistics	*Nodes*	17468	18326
	Elements	16313	16937

Each element of the Mesh integration network, was proportioned so that the number of nodes allocated be sufficient for the purpose of generating a network as thin as possible in the interest areas. The Mesh grid of the two cases is highlighted in Figures 3 and 4. After the generation of the integration network, 17468 nodes resulted for the NBC case and 18326 nodes for the MBC case (Table 1).

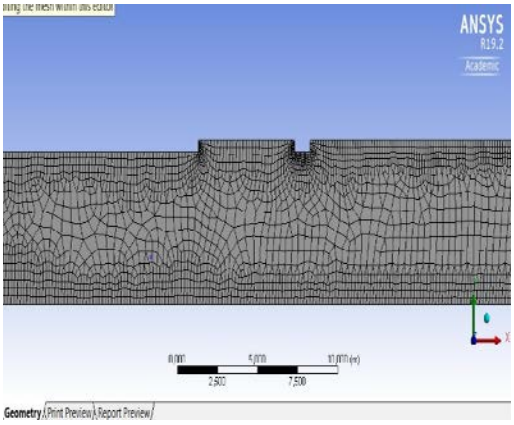

Fig. 3. Integration network - NBC case

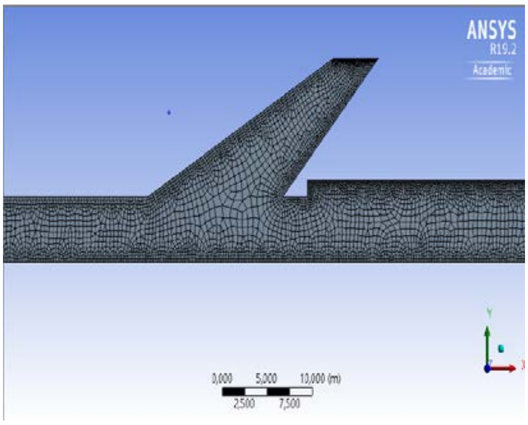

Fig. 4. Integration network - MBC case

In Tables 2 and 3, the on edge conditions and settings carried out in Fluent are presented for the purpose of simulating the two cases.

Table 2

Boundary conditions – NBC Case

Zone Name	Boundary	Settings	
Inlet	*Inlet_ velocity*	Velocity Specification Method	Magnitude
			Normal to Boundary
		Velocity Magnitude [m/s]	16.6 m/s (constant)
		Reference to Frame	Absolute
Outlet 1	*Pressure_outlet*	Backflow Reference Frame	Absolute
		Gauge pressure [Pa]	0 Pa (constant)
		Backflow Pressure Specification	Total Pressure
Wall	*Wall*	Adjacent Cell Zones	Surface Body
		Wall Motion	Stationary
		Wall Roughness - Model	Standard

Table 3

Boundary conditions – MBC Case

Zone Name	Boundary	Settings	
Inlet	*Inlet_ velocity*	Velocity Specification Method	Magnitude
			Normal to Boundary
		Velocity Magnitude [m/s]	16.6 m/s (constant)
		Reference to Frame	Absolute
Outlet 1 Outlet 2	*Pressure_outlet*	Backflow Reference Frame	Absolute
		Gauge pressure [Pa]	0 Pa (constant)
		Backflow Pressure Specification	Total Pressure
Wall	*Wall*	Adjacent Cell Zones	Surface Body
		Wall Motion	Stationary
		Wall Roughness - Model	Standard

Table 4

Definition of conditions of operation

Average air speed at system input	[m/s]	v_m = 16.6 m/s
Operating pressure	[Pa]	P = 101.325 Pa
Air density	[kg/m^3]	ρ = 1.225 kg/m^3
Reference air temperature (constant)	[k]	T = 298.15 K
Dynamic viscosity (constant)	[kg/m-s]	η = 1.7894 x 10^{-5} kg/m-s

The properties of the material used (air) were set down in the Fluent program. In the simulations carried out, the fluid is considered to be incompressible, operates at a temperature of 298.15 K and the operation pressure was set down at 1 atm. (101.3251 Pa). Fluent shall use this internal pressure for all types of fluid flow. Fluid properties are shown in Table 4.

For the purpose of determining the type of air flow through the system (laminar or turbulent), formula Reynolds' number was used:

$$Re = \frac{\rho \cdot v_m \cdot D_t}{\eta} \qquad (1)$$

Where: D_t [m] represents the tunnel diameter, v_m [m/s] represents the average fluid speed in the entry section, η [Pa s] represents the dynamic viscosity, ρ [kg/m^3] represents the fluid density.

In the system (NBC), in line with Reynolds' number, the air flow is not a laminar one, but rather a turbulent one.

In the Fluent setup was selected the option: model - k - ε (2eq). The k- ε model is the most common model used in Computational Fluid Dynamics (CFD) to simulate mean flow characteristics for turbulent flow conditions. The k- ε model it is a two-equation model that provides a general description of the turbulence using two transport equations (PDEs) one for turbulent kinetic energy (*k*) and the other for dissipation rate of the turbulent energy (*ε*). The k- ε model uses the gradient diffusion hypothesis to link Reynolds constraints of gradient velocity and turbulent viscosity gradients [14].

Standard k - ε model is known in the speciality literature a being the Sharma–Launder model. The original impetus for the K-epsilon model was to improve the mixing-length model, as well as to find an alternative to algebraically prescribing turbulent length scales in moderate to high complexity flows [15, 16].

3. Measuring Average Air Speed

Measurements on air speed "in situ" were carried out at Piaţa Unirii 2 Metro Station in Bucharest. In Figure 5, the scheme for the subway station with measurements points considered to be optimal for the measurement of average air speed, generated by the train movement through subway galleries, is presented. P1 is the measuring point located at the exit of the tunnel and P2 is the point of measurement located at the platform level after the buffer chamber.

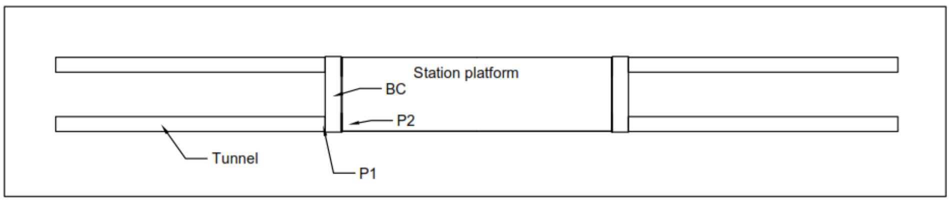

Fig. 5. Points where in situ measurements for the air speed were carried out - Piaţa Unirii 2 Station

The measurements regarding the average air speed were executed “in situ”, with a digital Data Logger (Pacer Instruments DA40V model) anemometer (Fig. 6).

Fig. 6. Anemometer – Model DA40V

The air piston speed during measurements with the portable anemometer reached a maximum of 16 m/s. It is worthy of note that the speed of the subway train in Bucharest is between 0 - 80 km/h, depending on the traffic system or on the areas with restrictions imposed in the tunnel. For this purpose, the air piston generated by the movement of the train in the tunnel is directly proportional to the speed of the subway train. For the Fluent CFD simulation of the two cases, an interest was presented for the maximum speed recorded by the anemometer during a maximum of the air piston in the measurement points in Figure 5.

Table 5

Technical specifications for the anemometer Model DA40V

Range		
Velocity	AP275 probe: 40 - 7800 FPM (0.2 - 40.0 MPS)	AP100 probe: 60 - 6800 FPM (0.3 - 35.0 MPS)
Volume flow rate	0.0 - 9999 ft^3/min (CFM) or 0 – 9999 m^3/h (CMH)	
Accuracy	1.0% of reading ±1 digit	
Resolution	1 FPM or 0.01 MPS	
Operating Temperature	Instrument: 32 to 125˚F (0 to 50˚C) Probes: -4˚ to 210˚F (-20˚ to 98.9˚C)	

4. CFD simulation results for NBC and MBC cases

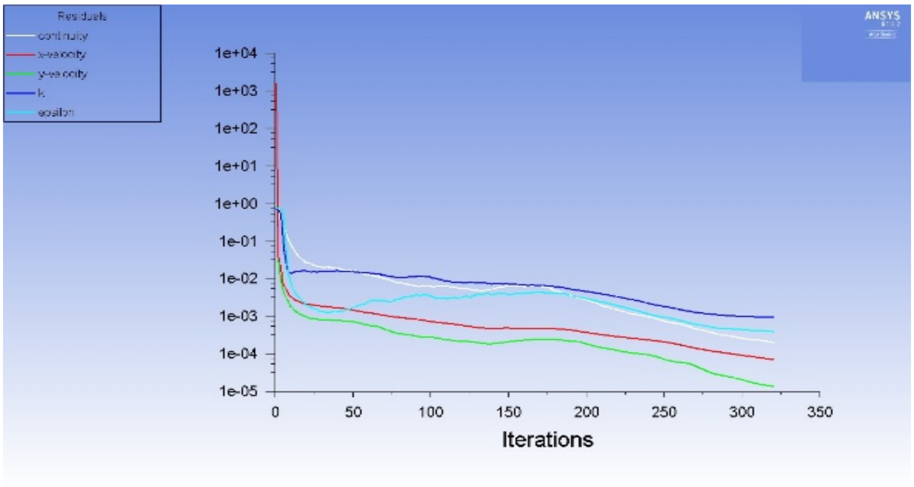

Fig. 7. Residues display for the NBC case

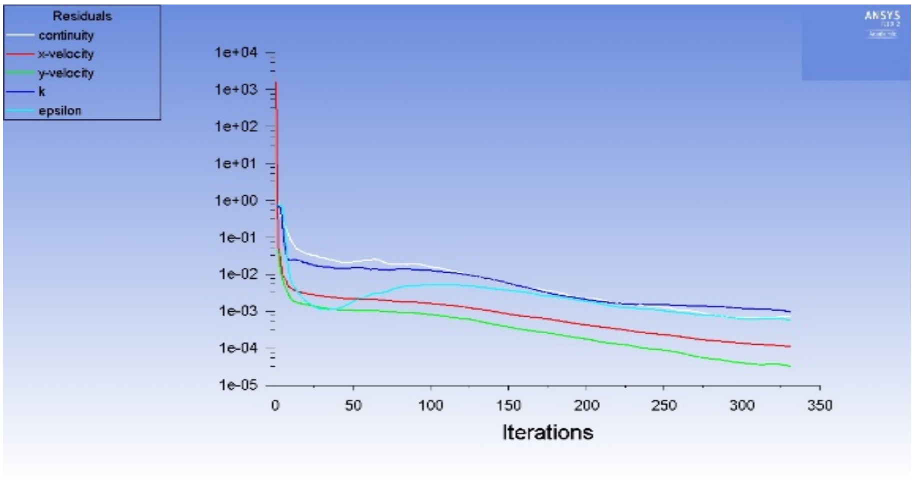

Fig. 8. Residues display for the MBC case

The results of CFD simulation in Figures 7 and 8 the residue charts for the two cases are presented, where they decreased below the criterion of convergence of 10^{-3} after 321 iterations in the NBC case, Fig. 7 and 332 iterations in the MBC case, Fig. 8. The residue represents a measure of the manner in which the current solution satisfies the discrete form of each equation.

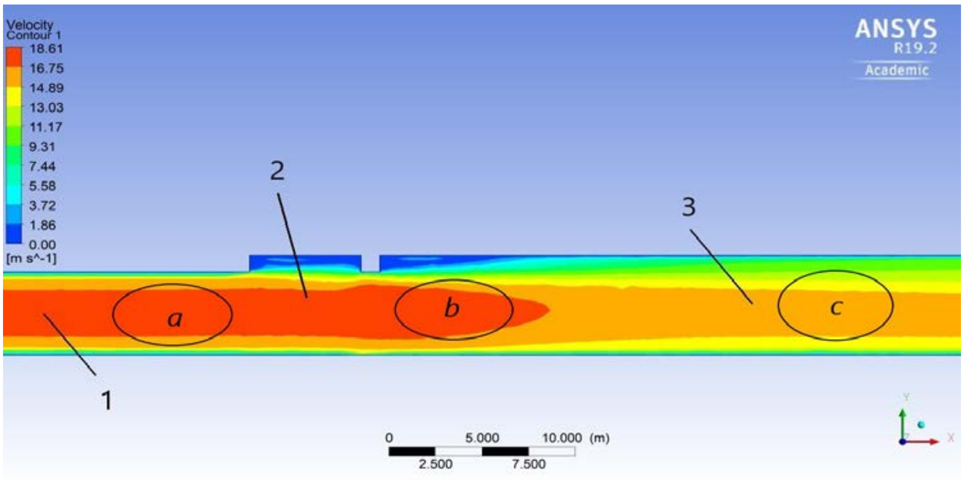

Fig. 9. Air speed contour for the NBC case

In Figure 9 the areas of interest regarding the evolution of the air piston speed through the system of case NBC are indicated: 1) the tunnel area where air speed in the tunnel axis reaches 16.6 m/s, 2) the buffer chamber area where one can notice that the air speed suffer small modifications due to the size of the buffer chamber, 3) the station platform area where one can notice a decrease in the air speed reaching 15 m/s in the platform axis and near the walls the speed decreases significantly. The evolution the air piston: a) the air piston inside the tunnel, b) the air piston at the entrance to the station, and c) the air piston in the subway station.

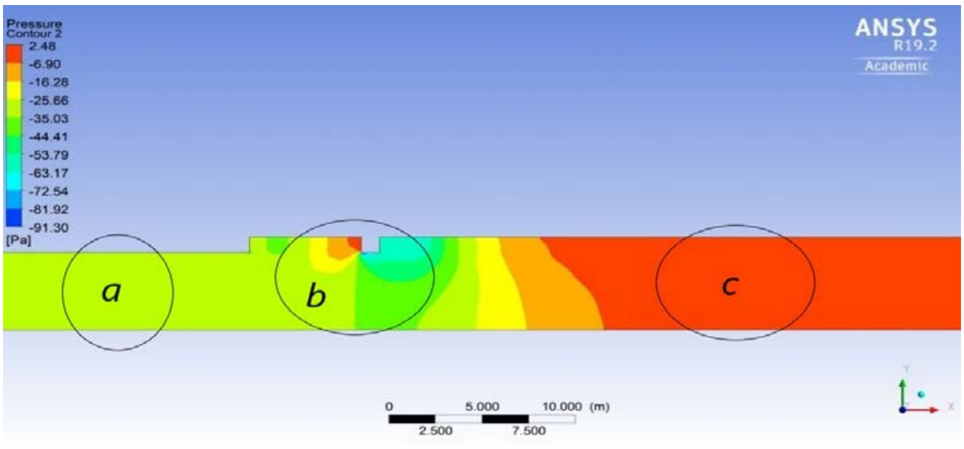

Fig. 10. Air pressure contour for the NBC case

In Figure 10 one can notice the profile of the air pressure in the NBC system, which in the tunnel area reaches negative values of -25Pa so that later in the platform area it reaches positive values of 2.4 Pa. The evolution of the air piston pressure in the NBC system: a) the air pressure inside the tunnel, b) the air pressure at the entrance to the station, and c) the air piston pressure in the subway station.

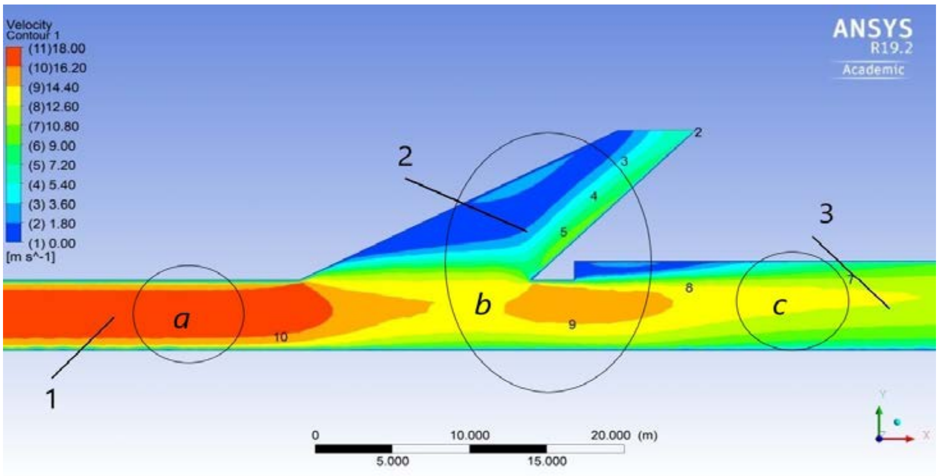

Fig. 11. Air speed contour for the MBC case

In Figure 11 the profile of the air piston circulating through the MBC case system is presented, presenting the following areas of interest: 1) the tunnel area where air speed in the tunnel axis reaches 16. 6 m/s, 2) the buffer chamber with the air intake, where one can observe a deviation of the air flow where upon exiting the system through this deviation reaches 5 m/s, 3) the station platform area where one can notice a decrease in the air speed in comparison with the NBC case. In this case, the air speed decreases towards 7 m/s at the level of the subway station. The evolution the air piston of the MBC case: a) the air piston inside the tunnel b) the air piston in the buffer chamber and at the entrance to the station, and c) the air piston in the subway station.

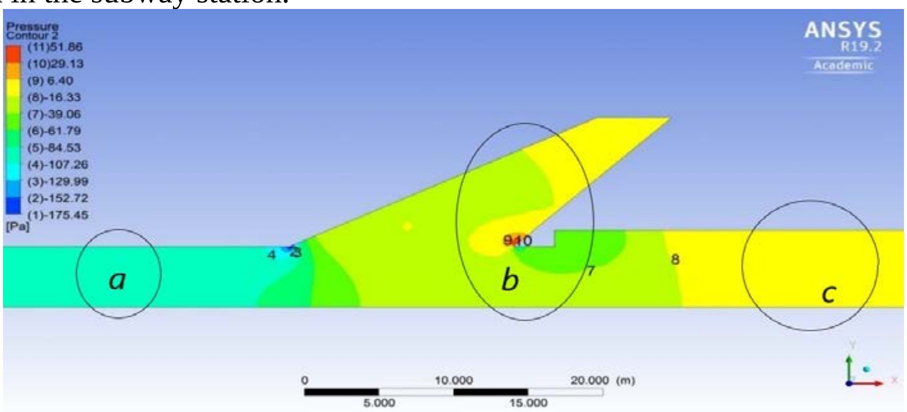

Fig.12. Air pressure contour for the MBC case

In Figure 12 one can notice the profile of the air pressure in the MBC system, which in the tunnel area reaches negative values -107.26 Pa. In the buffer chamber, air pressure reaches the negative value of -20 Pa, then stabilising in the platform area to a pressure of -16. 3 Pa. The evolution of the air piston pressure in the MBC system: a) the air pressure inside the tunnel, b) the air pressure in the buffer chamber and at the entrance to the station, and c) the air piston pressure in the subway station.

Table 6

Mass flow obtained following the simulations in cases NBC and MBC

CASE MBC		CASE NBC	
Name Zone	Mass Flow Rate [kg/s]	Name Zone	Mass Flow Rate [kg/s]
Inlet	101.49	Inlet	101.67
Outlet 1	- 83.58	Outlet 1	-101.67
Outlet 2	-17.91	-	-
Net	0.0016	Net	0.0047

In Table 6 one can notice the mass flow rate obtained following the simulations where the net mass flow is near to zero. According to the continuity equation, the net mass flow rate must be zero. It can be said that the solutions found by the Fluent are good enough to be considered valid for the two NBC and MBC cases.

5. Conclusions

This paper intended to achieve a means through which part of the air flow generated by the train movements through subway galleries, prior to it entering the passenger station, can be deviated. The article proposes a means of deviating the air piston modifying the buffer chamber, inserting a deviation of 45 degrees.

In the first NBC simulation, one can observe how the air piston generated by the train movement through the subway gallery continues its linear trajectory in the subway station with a relatively constant speed. The air volume of the air piston shall be found in the subway station on the level. From the second MBC simulation, one can observe that the introduction of the air intake creates a partial deviation of the air piston towards the outside of the subway, thus achieving a reduction of the air flow entering the subway station at the platform level.

In conclusion, the two 2D models of the subway station, numerically simulated in ANSYS CFD, confirmed that the air piston can be deviated and by it improving the comfort conditions for the passengers in the subway stations.

The simulations of the two NBC and MBC cases created a starting basis for a new research which shall involve 3D CFD simulations with results much closer to reality. The simulations shall lead to a better understanding of the phenomena which entail the piston effect and the design of certain stations that would reduce the discomfort of the passengers waiting for subway trains.

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