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Comparative Study of Intake and Exhaust Air Flows of Different Commercial Air Valves

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Abstract

This work aims to study in detail the methods of experimental characterization of air valves. In the first part, different experimental techniques are compared to the measurements made in the Air Valves Test Bench built by Bermad CS at its factory in Evron (Israel). The second part deals with the study of a collection of commercial air valves from different manufacturers. Finally, the Wylie and Streeter discharge coefficient C_d for air valve characterization [1] has been obtained. The results have been also compared with a simplified proposed model representation of the air valve.

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Keywords: Air valves, Test bench, Entrapped air, Air flow curves, Laboratory

1. Introduction

Entrapped air is one of the main problems in water distribution networks management. Air pockets inside the pipes cause problems in the normal network operation: reduction of the effective pipe cross section; additional head losses; decreased performance in pumps; noise and vibration problems; internal corrosion of pipelines due to the oxygen present in air; loss of efficiency in certain types of filters and important errors in micrometers, not specifically designed to carry a biphasic flow.

The presence of air also creates significant difficulties in the startup and shutdown process of the system. Entrapped air in pipelines has a high compressibility. Therefore, the acceleration or deceleration of the transient flow can result in the occurrence of high pressures. Such pressures can sometimes be much higher than those caused by transients without the presence of air (power failure in pumps or rapid closure of valves).

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To avoid the problems caused by the air inlet and outlet, air valves are installed in the water distribution systems. Once installed, air valves become a part of the system interacting with other system components (pipes, valves, pumps).

The design and selection of air valves requires knowledge about their behavior. This behavior is characterized by the intake or exhaust flow rate through the air valve depending on its differential pressure. Establishing the operating limits of every air valve is also a part of the air valves characterization. Definitely one of the main problems related to the operation of these devices is the kinetic closure. It occurs when the air valve float closes due to certain conditions of the air flow. This closure can be due to an excessive differential pressure across the float or due to and excessive drag force caused by a too high air velocity. In any case, this closure must be studied in detail because it can generate significant transients that can damage the water distribution systems.

A widespread practice of some engineers is to consider the nominal size of the air valve as its characteristic parameter. Thus, it is common to find projects, specifications indicating only the air valve nominal diameter without specifying in any way its design conditions (mass flow rate or differential pressure). American standards [2] establishes that the minimums cross section along the air valve must be the inlet one. Therefore, most manufacturers in all over the world design their valves considering this restriction. In Europe, the reference standard is EN 1074-4 defined by the CEN [3].

The main objective of this work is to study comparatively the behavior of different air valves. Thus, a comparative analysis of the different air valves testing techniques is performed. Later one of these techniques is used to study a broad range of air valves of the same diameter. From these results, a comparative analysis of the air valves characteristic curves is performed. In addition, a validation of the air valves characterization mathematical models is done.

2. Experimental set-up for testing air valves

The main problem related to the performance test of the air valves, is the volume of air that is necessary to flow into the test system. An 80 mm (3 inch) nominal diameter air valve may require a flow rate about 3000 standard m^3/h. This flow grows a lot with larger sizes. A 100 mm air valve may require about 8000 standard m^3/h, while a 300 mm valve may require a flow up to 72 000 standard m^3/h.

At present there are two main techniques to test the pneumatic characteristics of an air valve. The first one is based on storing large amounts of air in high pressure air vessels. Subsequently, the air is gradually released through a system that reduces the pressure to the air valve operating pressure.

Even considering that the minimum for each testing time is approximately one minute, the minimum volume required for these tests is great. With a storage pressure between 9 and 10 bar, the minimum volume to test a 4-inch air valve is about 23 m^3. In the case of a 12-inch air valve, this minimum volume is greater than 200 m^3.

Fig.1. Bermad's Air Valves Test Bench.

An alternative option for testing valves is to have a blower with enough capacity to supply the air needed during the tests. The problem lies in the size and power of the blower. For the case of a 12-inch air valve, the blower would need a power about 1 MW and weighing over 40 tons.

Both technologies are highly effective for testing air release, but the first one is very inefficient for testing pressures below atmospheric pressure. Therefore, this method is not very suitable for testing air intake.

For the development of the experimental phase of this work, the Bermad's Air Valves Test Bench has been used. This bench (Fig. 1) was built by the company Bermad CS at its factory in Evron (Israel). It has a blower of 315 kW with intake and exhaust maximum air flow capacity of 16,320 standard m^3/h (20 Celsius) at 52kPa. The control devices of the test bench allow testing air valves with diameters from 2 to 12 inches in a continues process that allows measuring the air flows during the entire pressure range of up to 0.5 bar (pipeline filling) and -0.5 bar (pipe line drainage and vacuum condition).

Schematically the test bench used meets the requirements of European standards (Fig. 2), including minimum distance requirements between the elements. Pressure source is formed by the blower and the control valves connecting both the test line with the air valve with the air flow thermal mass meter. Both pressure transducer and thermal mass flowmeter has been previously calibrated by certified laboratories. Valve configuration is different for release or vacuum tests. In case of air exhaust, the blower is at the beginning of the installation and the air valve on its end. In case of air intake, system is reversed, with the air valve at the beginning and the blower at the end.

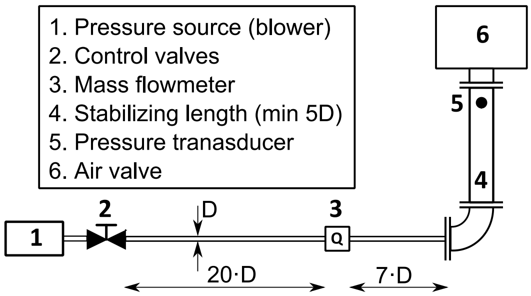

Fig.2. Experimental set-up used during the tests according to the CEN standards.

Air valves have three different functions:

- *Vacuum (air inlet)*. Intake of large quantities of air when the pressure inside the pipe is less than the atmospheric pressure. This is the case of emptying water pipelines.
- *Release (air outlet).* Removal of large amounts of air when the pressure inside the pipe is higher than the atmospheric pressure. This is the case of filling pipelines.
- *Relief.* Removing small amounts of air that accumulates on the high points. Occurs during normal system operation.

To make this work, nineteen different air valves models were selected. These models cover 13 manufacturers from 9 different countries (Austria, Belgium, France, Germany, Israel, Italy, Spain, United Kingdom and USA). In order to be able to compare the different air valves, there was necessary to select a reference common size. In some preliminary studies [4] a 50 mm nominal size diameter was considered as initial reference value. However, preliminary results [5] advised to increase the size of the study to 80 mm (3 inches) to consider a broader manufacturers range. During this work only release and vacuum functions of air valves are considered.

3. Air valves characterization

The characterization of an air valve consists in determining the air inlet and outlet capacity for every differential pressure. Many models related with entrapped air use the air valve representation proposed by Wylie and Streeter [1]. The equations of this model for air outlet are:

$$\begin{aligned} G &= C_{d,exp} A\; p_t^* \sqrt{\frac{7}{RT_t}\left[\left(\frac{p_{atm}^*}{p_t^*}\right)^{1,4286} - \left(\frac{p_{atm}^*}{p_t^*}\right)^{1,714}\right]} && \text{if } p_t^* \le 1.8929 \cdot p_{atm}^* \quad \text{(subsonic flow)} \\ G &= C_{d,exp} A\; \frac{0,686}{\sqrt{RT_t}} p_t^* && \text{if } p_t^* > 1.8929 \cdot p_{atm}^* \quad \text{(supersonic flow)} \end{aligned} \tag{1}$$

Moreover, equations for air inlet are:

$$\begin{aligned} G &= C_{d,adm} A \sqrt{7 p_{atm}^* \rho_{atm}\left[\left(\frac{p_t^*}{p_{atm}^*}\right)^{1.4286} - \left(\frac{p_t^*}{p_{atm}^*}\right)^{1.714}\right]} && \text{if } p_t^* \le 1.8929 \cdot p_{atm}^* \quad \text{(subsonic flow)} \\ G &= C_{d,adm} A \frac{0.686}{\sqrt{RT_{atm}}} p_{atm}^* = \text{constant} && \text{if } p_t^* > 1.8929 \cdot p_{atm}^* \quad \text{(supersonic flow)} \end{aligned} \tag{2}$$

In the above equations, G is the mass flow rate across the air valve; p_t^* is the absolute pressure in the pipeline; p_{atm}^* is the absolute atmospheric pressure; R is the characteristic gas constant when it is considered as ideal; ρ_{atm} is the air density at atmospheric pressure; T_t is the temperature of air inside the pipe; A is the outlet cross section and $C_{d,exp}$ and $C_{d,adm}$ represent the values of the outflow and inflow discharge coefficient.

Fuertes et al. [5] presented an alternative air valves model considering an incompressible behavior of air. This model assumes that in areas of air valves normal operation, compressibility effects are lightweight and can be acceptable considering incompressible flow. The equations of this model with subsonic flow are:

$$\begin{aligned} G &= C_{v,exp}\sqrt{\Delta p \cdot p_t^*} && \text{Air outlet} \\ G &= C_{v,adm}\sqrt{\Delta p \cdot p_{atm}^*} && \text{Air inlet} \end{aligned} \tag{3}$$

In equation (3), $C_{v,exp}$ and $C_{v,adm}$ are the outflow and inflow characteristic coefficients of the air valve; and ΔP is the differential pressure.

4. Analysis of results

The comparative analysis of the behavior of the different air valves has meant the realization of 194 tests with 1672 measurements. Although the number of models considered in this study was 19, testing each of the models has been repeated several times in order to verify the repeatability of the results.

Due to the particularities of the system, some test limits in air valves have been established. These limits are set by the constraints of the system: maximum pressure in system and maximum power and torque in blower. However, the defined range allows analyzing thoroughly the normal operation area of the air valves tested. The limit in flow has been fixed in 3000 standard m^3/h. Meanwhile the highest levels of differential pressure across the air valve will be 0.5 bars for both release and vacuum tests.

Analysis of experimental data has been focused on the following aspects:

- Difference between the technical data provided by the manufacturer and the experimental data.

- Comparison of the maximum intake and exhaust air flow and determination of the air valve kinetic closure.
- Effect of different covers on the behavior of the air valve.
- Validity of the mathematical models to represent the air valves behavior.

4.1. Difference manufacturer data and experimental data

The analysis of the results shows a big difference between the manufacturer's data and experimental data in much analyzed cases. In some models, these differences are significant (Fig. 3, manufacturer R). The consideration of the manufacturer's data in these cases can lead to important wrongs in designs. These differences are greater for inflow than for outflow (Fig. 3, manufacturer E). Even some manufacturers that have a good representation of its air valve behavior expelling air have significant errors when they work with vacuum (Fig. 3, manufacturers M and E).

4.2. Extreme operating conditions of each valve

The extreme conditions of operation of a valve are given by two main factors: the maximum flows and the presence of kinetic closure. Table 1 lists the maximum flow points during the release test of every air valve. It also includes the maximum flow during the vacuum test. Finally, Table 1 also indicates the kinetic closure in the air valve. "No" in Table 1 means that the valve did not close within the defined workspace, (maximum flow 3000 m^3/h and maximum pressure 0.5 bar). It is not possible to say if these air valves may present kinetic closure at higher pressures or flows.

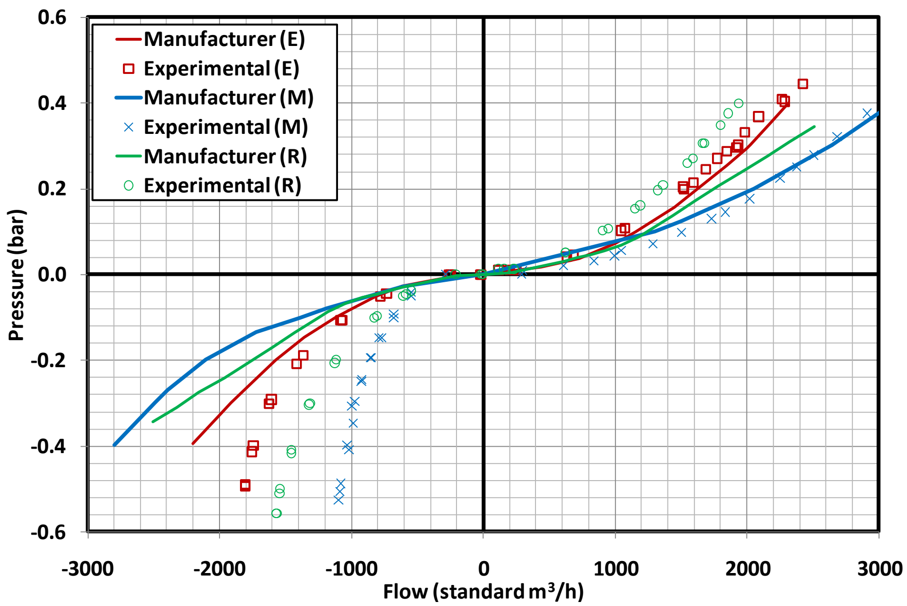

Fig. 3. Differences between manufacturer data and experimental data.

The results of the Table 1 indicate the wide range of valve operation. A significant number of valves present a kinetic closure point with low flows and pressures (B, H, I, N, P).

The results of the different air valve models at -0.5 bar are in a range from 435 to 2490, almost six times different. A designer which base his design on the need for air intake of 1500 std m^3/h for example only would be able to use 8 air valves. In the case that a designer recommended a specific air valves model to meet its air control requirement, it cannot be replaced with another one. Although two valves had the same nominal inlet, there is a risk that the system will not be protected according to the design requirements (since the new air valve might not have the required airflow capacity).

Table 1. Extreme results of air valves tested.

Model	Release Test (Kinetic Closure Point)			Vacuum Test
	Pressure (bar)	Mass Flow Rate (std m^3/h)	¿Kinetic Closure?	Max. Flow Rate at -0.5 bar (std m^3/h)
A	0.30	880	Yes	- 435
B	0.07	915	Yes	- 1473
C	0.46	2231	No	- 1719
D	0.29	1955	Yes	- 1825
E	0.45	2417	Yes	- 1812
F	0.46	2345	No	- 825
G	0.53	972	No	- 1359
H	0.11	1015	Yes	- 1493
I	0.14	1135	Yes	- 1648
J	0.51	846	No	- 830
K	0.27	3493	No	- 2128
L	0.52	900	Yes	- 688
M	0.38	2912	No	- 1096
N	0.02	420	Yes	- 1242
O	0.31	1300	Yes	- 1000
P	0.01	780	Yes	- 2490
Q	0.48	1178	No	- 650
R	0.40	1938	Yes	- 1568
S	0.33	3168	No	- 2260

4.3. Effect of different covers over the air valves.

An effect that has been specifically studied in this work is the influence of different covers installed on the same valve. The results are shown in Fig 4. Up to 4 different covers have been studied. Also the air valves behavior without cover have been analyzed. The curves obtained are clearly different. The most significant fact is that none of the manufacturers collect different characteristics for different covers on its technical documentation. That is, on the technical information provided by the manufacturer air valve characterization is unique regardless the cover used. This represents an important source of error that must be considered by engineers during the design.

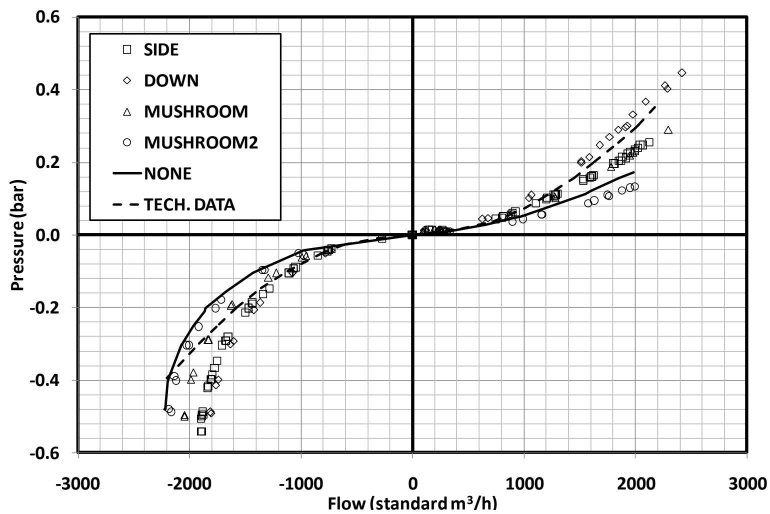

Fig. 4. Influence of the valve cover on its characteristic curve.

4.4. Mathematical model validation

After analyzing all the results, it is necessary to validate the air valve models. To validate each model an adjustment by quadratic regression of every characteristic has been performed. For the model proposed by Wylie and Streeter adjusted parameters were outlet and inlet discharge coefficients ($C_{d,exp}$ and $C_{d,adm}$). For the incompressible proposed model adjusted parameters were the characteristics coefficients $C_{v,exp}$ and $C_{v,adm}$.

Statistical analyzes and their errors are shown in Table 2. In this table, the error of each parameter is the maximum relative error. In the model of Wylie and Streeter there is a great difference between the values of the discharge coefficient obtained for both air outlet and air inlet. This model fits well the majority of models for air inflow. For outlet air the model generates important errors and the model should not be used for a large number of the tested models.

Table 2. Validity of the air valve mathematical models.

Model	Wylie & Streeter model				Incompressible proposed model			
	Air outlet		Air inlet		Air outlet		Air inlet	
	$C_{d,exp}$	Error (%)	$C_{d,adm}$	Error (%)	$C_{v,exp}$	Error (%)	$C_{v,adm}$	Error (%)
A	0.21	9.7%	0.11	11.3%	1358	6.2%	641	13.8%
B	0.49	34.6%	0.37	12.4%	3534	33.7%	2071	13.9%
C	0.35	71.9%	0.40	64.8%	2294	66.9%	2348	52.6%
D	0.48	10.6%	0.49	4.3%	3209	7.8%	2827	14.4%
E	0.47	20.9%	0.49	3.6%	2997	17.2%	2834	13.7%
F	0.42	46.8%	0.22	11.2%	2919	44.3%	1246	21.5%
G	0.17	35.3%	0.36	7.2%	1079	41.8%	2065	13.6%
H	0.37	26.6%	0.39	9.0%	2579	24.8%	2159	12.1%
I	0.41	11.2%	0.44	7.5%	2904	9.4%	2406	11.6%
J	0.14	139.8%	0.22	8.3%	969	149.7%	1211	13.1%
K	0.93	10.0%	0.58	1.9%	6183	9.2%	3415	18.8%
L	0.14	47.7%	0.17	23.3%	966	58.1%	996	31.1%
M	0.65	7.4%	0.30	11.4%	4259	9.7%	1717	21.2%
N	0.36	40.3%	0.34	2.1%	2606	40.2%	1892	16.8%
O	0.31	18.8%	0.26	11.3%	2023	15.7%	1426	11.4%
P	0.81	23.3%	0.70	3.0%	5896	23.2%	4122	13.0%
Q	0.18	39.5%	0.17	8.0%	1214	34.6%	980	14.6%
R	0.41	19.1%	0.41	10.4%	2646	15.7%	2250	11.0%
S	0.76	26.6%	0.62	3.5%	4976	23.5%	3616	14.1%

In the proposed model, considering the incompressible flow, the results are significantly different. The errors for air outlet outflow are significantly lower. In contrast, the errors for inlet air are slightly higher than the error of the model proposed by Streeter and Wylie. In short, proposed model can be a valid alternative model at least for air outflows.

5. Conclusions

The main conclusions drawn from this study are:

- Although all air valves included in the research have the same nominal inlet size (3 inch / 80 mm), there are large differences between the intake and exhaust maximum air flow. This clearly shows that it is not enough to specify the size of an air valve by its nominal inlet to define it properly. The design specifications of the engineers in their projects should include not only the size of the valve but also its design features (air flow and differential pressure).
- The kinetic closure is a critical parameter for an air valve selection. The air valves tested have very different behaviors. Some models have extremely low kinetic closures, which can influence the filling requirements of the installation. A selection of an air valve with a low kinetic closure can generate important pressure surges during

the pipeline filling. In any case, it is a parameter that must be known by engineers for their projects and that is not usually on the information provided by the manufacturer.

- It is necessary to review in detail the information that manufacturers offer their valves. It is common to find discrepancies between manufacturer's technical data and its real behavior. Also, the technical documentation of some manufacturers do not reflect information about the kinetic closure or the different kinetic behavior of its air the valves with different covers (side, down, mushroom).
- Streeter and Wylie's mathematical model for air valves has been ineffective to represent its behavior, mainly during the air outlet. The incompressible flow model proposed has been very effective to represent the behavior of air outlet. Its effectiveness was less for the air inlet.

This work represents an important starting point in improving the air valves characterization techniques in order to allow and increasing optimization use of air valves in water distribution networks. The experimental results will make easier this research and can be a warning for engineers responsible for the design and operation of water distribution networks.

Acknowledgements

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