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The effect of the air duct tightness on the stability of the indoor air parameters

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Abstract. The present study aimed to determine the impact of a gradual and lineal increase of the air duct leakage factor on various indoor air stability parameters in ventilation systems across the following scenarios: 1) air leakage effect on the air pressure and volume; 2) air leakage effect on the indoor air parameters when the ductwork passes through an uninsulated and unheated premise. A galvanized steel air duct was used for the air leakage measurement sessions, and orifices were cut in the duct before each subsequent measurement session, thus, consecutively decreasing the air tightness factor of the duct over the measurement sessions. The results indicated that the ductwork air tightness affects the stability of the air parameters such as air temperature, relative humidity and CO_2 concentration, however, up until certain point, the impact was either non-detectable or negligible. The transition in the behavior of the air stability parameters occurred in line with the introduction of orifices 4→5, resulting in perceptible effects on air pressure, volume etc. Although, this factor may be attributed to the errors caused by low instrument sensitivity or by relatively small number and size of the orifices, authors suggest that minor air duct leakage such as presented in this study may result in the disruption of air stability parameters, which in certain instances is critical.

1. Introduction

The goal of the ventilation air ductwork is to transport the fresh air mass to ensure the required indoor air quality parameters in buildings' premises. The efficiency of the air transportation in the duct depends on the three main factors:

1. the cross-sectional shape of the duct (usually round or square ducts);
2. the material the duct is made of (galvanized steel, aluminum zinc, corrugated plastic, fabric etc.);
3. the pressure losses (velocity and friction losses).

However, to ensure that a ventilation system operates properly and maintains the required air parameters, it is of great importance to pay particular attention to the quality of the air ductwork installation and connection. Even minor permanent air leakage from the ductwork may affect the operation of the whole ventilation system and its long term efficiency, if it's not detected or not taken care of. There are number of factors, why leaking air ducts negatively affect the operation of the ventilation system and occupants' well-being.

Reduction of the air tightness in the ducts has a negative effect on the overall operation of the ventilation system, as the ventilation system becomes difficult to operate and control, due to numerous discrepancies between the designed and the actual air volume the system is supposed to transport and deliver.

Also, due to air leakage in the ducts, the fans in the air handling units have to operate at higher loads which leads the system to be inefficient, as the fans have to operate at higher capacity and consume more energy to deliver the same amount of air to the premises. This translates into a significant increase in energy costs [1], [2]. For instance, the energy consumption to run fans in the system with ductwork airtightness class C is up to 30 % higher than that of the class A [3]. As per the case study conducted for a pharmaceutical plant,

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where ductwork airtightness is imperative, the associated costs of the excessive air leakage in the ductwork would come out to over 1 million USD over the life cycle of the plant [4].

On the other hand, if the air leakage in the ductwork occurs, and the fans are not equipped with frequency converters (employed mainly in demand controlled ventilation systems such as CAV, DCV and VAV) to operate at higher capacity in order to compensate for the leaked air volume [5], the premises will experience the shortage of fresh air supply, therefore incurring deterioration of the indoor air quality (IAQ) and subsequent health concerns associated with the poor IAQ [6].

In addition, leaking air ducts may cause serious health hazard where maintaining strictly controlled environment is of utmost importance [7], [8]. In improperly installed and/or leaking air duct systems, exhaust air can leak into the supply air, causing unpleasant smells or even exposure to polluted air and poisonous gaseous particles [9], [10]. This applies to healthcare facilities, industrial kitchens, pharmaceutical factories etc.

If an uninsulated and leaking air duct passes through an unheated space, condensation may occur where the air leakage takes place, causing moisture build-up [11], [12] that in the long-term can deteriorate construction materials [13], [14] and induce mold growth that is known to have adverse effects on human's respiratory system [15], [16].

Another issue that stems from poor tightness of the air ductwork is the excessive heat loss [2], [3], [17], which greatly impacts energy consumption for the heat transfer in the ventilation systems' heat exchanger coils [18].

As such, it is critically important to comply with the air duct tightness criteria when it comes to design and, more so, installation of ventilation system ductwork. Furthermore, regular system monitoring serves to detect the occurrence and potential sources of air leakage, and subsequently prevents the excessive energy consumption [19] and poor indoor air quality the building occupants may be exposed to [20].

This study aims to determine the impact of a gradual and lineal increase of the air duct leakage factor on the various parameters in ventilation systems across the following scenarios:

- scenario 1 – effect on the ventilation system operational characteristics (with regards to air pressure and air volume);
- scenario 2 – effect on the indoor climate parameters (when leaking air duct passes through an uninsulated and unheated premise);

The current study contributes to an existing knowledge on the adverse impact of ventilation system air duct leakage on the energy efficiency and indoor air quality (IAQ) however, it also presents a full-scale test approach by looking into two different scenarios and assessing the air leakage impact factor by increasing the leakage degree linearly and in gradual increments.

2. Methods

A galvanized steel air duct of 3.25 m in length and 125 mm in diameter was used for the air leakage measurement sessions, referred to as the "leaking duct". An orifice of 6 mm in diameter was cut in the duct before each subsequent measurement session, thus, consecutively decreasing the air tightness factor of the duct. In total 11 measurements were carried out for each scenario, resulting in 11 orifices at the last measurement session.

Scenario-1

The "leaking air duct" test system was set up in a specially designed test chamber. The air temperature in the test chamber was kept at +22.8 ^{o}C and the relative air humidity was kept at 19.7%. Air was blown into the duct by a duct fan. Air pressure differential was measured on the air damper and an air flow rate was measured at the outlet end of the duct during each measurement session.

Scenario-2

The "leaking air duct" was placed into the test chamber which represented a dry, unheated, uninsulated and non-residential premise without active heat loads (such as storage space or auxiliary room). An air stream of RH 50−55 % was blown into the air duct – the relative air humidity, temperature and carbon dioxide concentration (ppm) were measured in the test chamber throughout the session. Based on the results, the effect of the airduct tightness on the indoor climate of the premise it passes through was determined.

Scenario-1

The aim of scenario-1 was to determine the effect of air duct tightness on the ventilation system's pressure and air volume. For this purpose, a ductwork system shown in Fig. 1 was setup.

Table 1. Parameters of the tested "leaking" air duct.

Length, mm	Diameter, mm	Thickness, mm	Surface area, m^2	Orifice diameter, mm	Number of orifices
3250	125	0.7	1.28	6	1-11 *

* The orifices in the air duct were cut by an increment of 1 orifice for every subsequent measurement, i.e., 1 extra orifice added for each additional measurement, resulting in total of 11 orifices after 11 measurements.

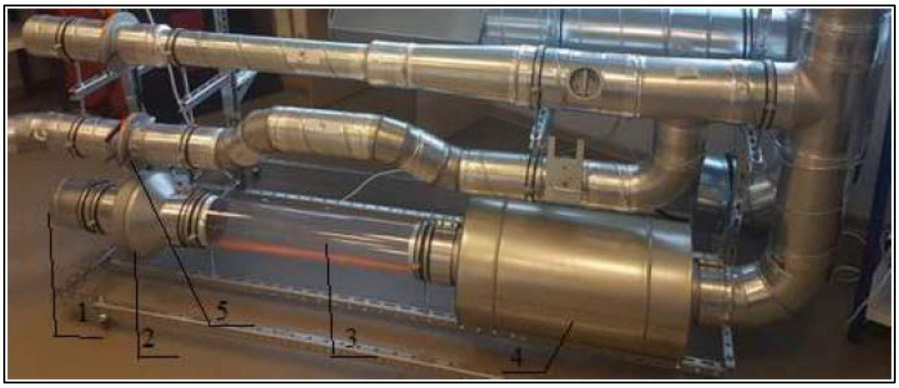

Figure 1. A ductwork system setup for scenario-1 (see the corresponding legend in Figure 2).

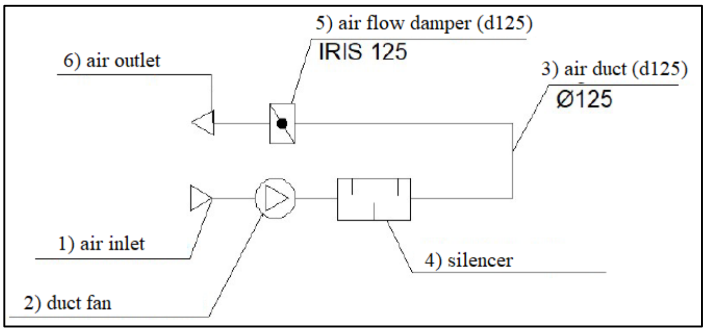

Figure 2. The schematic design of the test setup.

Scenario-2

In the following scenario, a condition of the leaking air duct passing through an unheated premise was tested, to see how a leaking air duct affects indoor parameters such as air temperature and relative humidity of the premise, if these parameters differ in the both environments (i.e., air duct and the test chamber). To carry out the measurements within the current scenario, the air duct was placed in a test chamber, that represented an unheated, uninsulated and non-residential premise (Fig. 3).

A question to be answered after the completion of the measurements and analysis of the test results: Is there a risk of mold development due to an excessive moisture build up in an unheated premise by an air leakage from a ductwork?

Table 2. Geometric parameters of the test chamber.

Length, m	Width, m	Height, m	Volume, m^3
3.34	2.5	3.0	25.05

Figure 3. The system setup for scenario-2 (test chamber).

The procedure of adding orifices in the leaking air duct was similar to the procedure outlined in scenario-1. As such, 11 measurements were conducted. The test chamber air quality parameters before the test run are shown in Table 3.

Table 3. Air quality parameters of the test chamber.

Temperature, ºC	Relative humidity, %	CO_2 concentration
22.8	19.7	877

3. Results and Discussion

Scenario-1

The results for scenario-1 are compiled in Table 4.

Table 4. Results for scenario-1.

Sample #	Number of orifices	Total relative orifice diameter, mm	System pressure, Pa	Air volume, l/s
1	1 x 6 mm	6	155	19
2	2 x 6 mm	12	155	19
3	3 x 6 mm	18	155	19
4	4 x 6 mm	24	155	19
5	5 x 6 mm	30	128	17
6	6 x 6 mm	36	127	17
7	7 x 6 mm	42	125	17
8	8 x 6 mm	48	122	17
9	9 x 6 mm	54	121	17
10	10 x 6 mm	60	119	16
11	11 x 6 mm	66	118	16

stable range

non-stable

The measurement results show that the system's pressure remains constant at 155 Pa until the fifth orifice is introduced in the air duct. At this point the pressure drops down to 128 Pa, and every subsequently added orifice induces further pressure drop, yet, at a very gradual and steady decline rate. The absolute pressure drop throughout the whole measurement section within scenario-1 is 33 Pa, however, the diagram can be divided into three separate segments – first (orifice 1→4) at which the pressure drop is not affected and thus remains constant value; second (orifice 4→5) with a steep pressure drop decrease when the fifth orifice is added; and third (orifice 5→11), throughout which pressure drops gradually in line with subsequent addition of orifices.

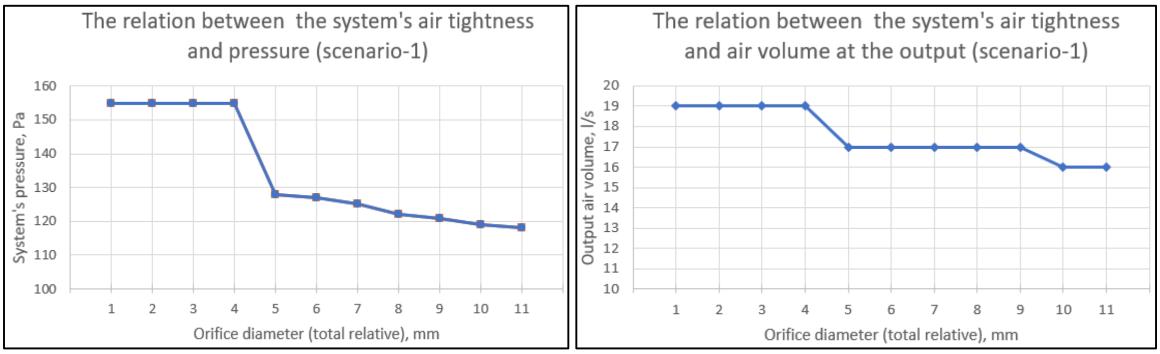

Figure 6. The system's pressure dependence (on the left) and the output air volume dependence (on the right) on the air duct tightness.

A similar pattern is observed with regards to the air volume at the outlet. Air volume remains at 19 l/s, however, once the fifth orifice is introduced, the air volume drops to 17 l/s. Subsequent addition of orifices did not affect the air volume at the provided instrument accuracy (the flowmeter of ±1.0 l/s accuracy was employed) until the tenth orifice was introduced, that caused a very slight air volume decrease to 16 l/s. As per the results, throughout the whole measurement section (after creation of 11 orifices in the air duct), the absolute air volume decrease was almost negligible (Δq = 3 l/s).

The results of scenario-1 imply that on a broader scale and in ventilation systems with large ductwork surface area, the air tightness is of critical importance. With compromised air tightness, the end user doesn't receive the designed air volume (Fig. 6), as the air pressure is not sufficient enough to transport and deliver the required air mass to the end-user.

Insufficient air volume, i.e., insufficient supply of fresh air into the premise causes an increase in carbon dioxide concentration, compromises the indoor air quality and leads to overall deterioration and occupant dissatisfaction with the indoor climate [21].

In case of CAV (constant air volume) systems, the frequency converter will increase fan output to keep the constant air pressure in the system and to ensure the delivery of sufficient amount of air to the end user, however, this results in an increase in energy consumption and thus, lower, system's energy efficiency [22], [23]. Poor ductwork air tightness also affects noise level in the ductwork and at the output terminals [24].

Scenario-2

Scenario-2 was run to determine how a poorly tight air ductwork affects the indoor climate of the premise it passes through. The leaking air duct was installed in an unheated and uninsulated chamber that represents a non-residential premise such as storage space or auxiliary room. Within this scenario the major indoor air quality parameters such as air temperature, relative humidity and carbon dioxide concentration were monitored in the test chamber throughout the 11-sample measurement session. The measurement results for scenario-2 are presented in Table 5.

Table 5. Results for scenario-2.

Sample #	Number of orifices	Total relative orifice diameter, mm	Relative humidity, %	Air temperature, ºC	CO_2 conc., ppm
1	1 x 6 mm	6	19.7	22.8	877
2	2 x 6 mm	12	19.7	22.8	877
3	3 x 6 mm	18	19.7	22.8	877
4	4 x 6 mm	24	19.7	23.0	877
5	5 x 6 mm	30	20.2	23.3	882
6	6 x 6 mm	36	21.0	23.4	1009
7	7 x 6 mm	42	21.2	23.4	1077
8	8 x 6 mm	48	21.7	23.5	1149
9	9 x 6 mm	54	22.2	23.7	1234
10	10 x 6 mm	60	22.6	23.8	1284
11	11 x 6 mm	66	22.9	23.9	1351

stable range (samples 1–4)

non-stable (samples 5–11)

Fig. 7 shows that scenario-2 developed a similar pattern to scenario-1 – no change in the air stability parameters until the introduction of the fifth orifice in the air duct. As the air duct tightness is being decreased further (orifice 5→11), the air temperature and relative humidity in the room increase at a steady growth pattern. This again shows that up until the forth orifice in the airduct, the overall big picture impact on the air tightness is somewhat negligible, while with the introduction of the fifth orifice and onwards (5→11), the air stability parameters are being affected steadily.

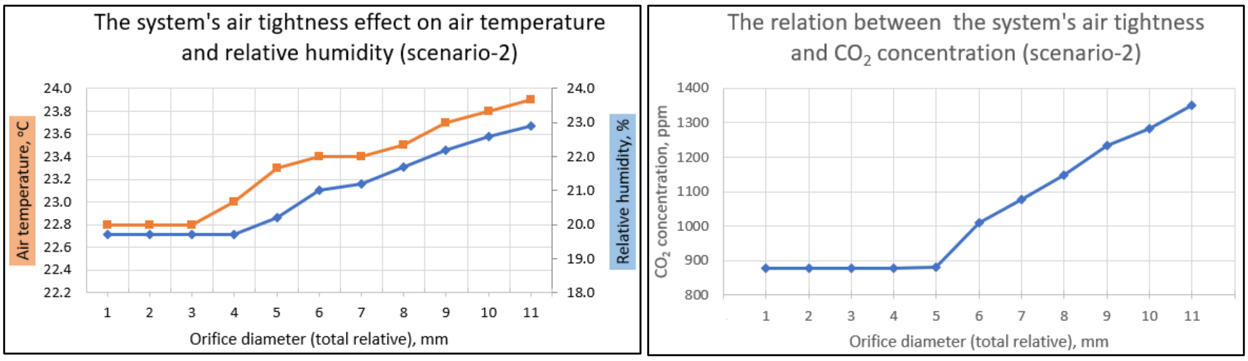

Figure 7. The air temperature and relative humidity dependence on the air duct tightness (on the left); The CO_2 concentration dependence on the air duct tightness (on the right).

The CO_2 concentration (Fig. 7. on the right) in the test chamber can be broken down to three development segments:

1. CO_2 concentration remains constant at 877 ppm throughout the introduction of orifices 1→4;
2. After the fifth orifice (5) is introduced, the CO_2 level rises insignificantly (884 ppm);

3. Throughout the creation of orifices 6→11, the CO_2 concentration increases continuously to reach 1351 ppm at the last sample.

The results show that ductwork air tightness affects the stability of the air parameters such as air temperature, relative humidity and CO_2 concentration, however, up until a certain point, the impact is either non-detectable or negligible. This suggests that a higher accuracy instruments are used in order to obtain a more accurate and detailed dataset. On the other hand, it is highly probable that orifices of 6 mm in size are relatively small to affect the instrument readings regardless of their accuracy or sensitivity, and, thus, there is no detectable effect on the system's operation and behavior, suggesting that some level of air duct leakage is always present and acceptable for that matter, and does not affect the system's operation in the long run [25], [26]. This correlates with a common understanding that no system is perfect and there is always some degree of system malfunction or drawback present. In order to obtain somewhat perceptible readings, either the orifice diameter has to be larger, or the number of orifices has to be higher (as in the current case).

Nevertheless, in the pursuance of the objectives established within the framework of the current study, the accuracy of the carried measurements is reasonably adequate and acceptable to infer broader conclusions relating to impacts on the systems' operating at bigger scale.

4. Conclusions

The study results contribute to the existing knowledge of an adverse effects on the energy efficiency and the IAQ parameters of a poor air duct tightness in ventilation systems. Within the frame of this study indoor air parameters such as air volume, pressure, temperature, relative humidity, CO_2 concentration and mineral-wool particle presence in supplied air steam were measured.

As per scenarios 1 and 2, a certain pattern of a stable and a non-stable range developed with regards to the measured air parameters. Introducing small size orifices of 6 mm in the ductwork did not trigger a detectable response in the indoor air quality parameters throughout the measurement sessions 1→4 (matching the number of orifices cut in the air duct). Perhaps this can be attributed to the lower-tier sensitivity and accuracy of the instruments used to measure air volume and pressure. However, in line with further increasing the number of orifices in the air duct (orifices 5→11), a gradual yet steady change in the indoor air parameters was observed (non-stable range). As per the presumptions, an increased air leakage factor translated in a lower pressure in the system and decreased air volume supplied to the end-user (scenario-1), while also adversely affecting air stability parameters when a leaked duct was placed in a test chamber representing an unheated non-residential premise (scenario-2). The IAQ parameter behavior throughout the creation of orifices 5→11 is rather an expected outcome. On the contrary, the system's unresponsive behavior throughout the introduction of orifices 1→4 is a rather peculiar finding. Authors suggest that the following factors may affect this: 1) low instrument sensitivity, unable to detect such an insignificant change in air pressure and volume; 2) orifices of 6 mm in size do not generate enough air leakage in the duct to cause reasonable fluctuation in air stability parameters up to a certain degree (in this study – up until the introduction of the forth orifice).

The results indicate that the ductwork air tightness affects the stability of the air parameters such as air temperature, relative humidity and CO_2 concentration, however, up until a certain point, the impact is either non-detectable or negligible. This suggests that a higher accuracy instruments have to be used in order to obtain a more accurate and detailed dataset. Also, decreasing the orifice diameter and increasing the number of orifices might present a better picture on how the air stability parameters are affected if an air tightness decrease occurs at very gradual increments across a multitude of measurements.

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