Reply to the comments of referee #1

The manuscript left me with mixed feelings. On the one hand, it contains interesting information about ice-drilling design and experiments. However, on the other hand, the information is not presented in a clear and logical sequence, and some important details are omitted. I believe that the article would benefit from major revisions before publication.

Thanks for your helpful comments. The manuscript has been carefully revised according to your suggestion.

General comments:

1. The title of the paper is too long and not very descriptive.

The title has been changed to "Experiences and Lessons Learned from Designing and Testing of an Air System and a Drilling Fluid Circulation System Adapted for Subglacial Bedrock Drilling in Antarctica". In the new title, the "experiences and lessons" is emphasized, and the two systems are emphasized to be used for subglacial bedrock drilling in Antarctica.

2. There is no information about the key technological elements of the drilling technology, such as the drill rig, drill pipes, drill bits, drilling fluid components, etc. Also, there is no information about the locations of the domestic and Antarctic test sites. Without this information, it is impossible to fully understand the process of drilling and problems.

The following sentences are added in the "Introduction" section to give more information about MPDS.

"*All the subsystems are modularly designed and can be disassembled into several parts with each one less than 4 tons for easy transportation by helicopter from ice breaker to polar ice sheet. Once arrived at ice sheet, all the subsystems can be integrated in a 20'' container and can be transported on ice sheet by sledge. All the subsystems were integrated in standard 20 ft container and could be easily moved on the ice surface by sledges. The drill rig is fully driven by a hydraulic system and can work with different drilling processes, such as air/drilling liquid reverse circulation drilling and wireline coring drilling. The drill-rod module is used for drill rod storage and is adjacent to the drill rig for easy transferring of drill rod in field. Air system is utilized to generate dry and cold compressed air*"

"*Double-wall drill rod made by aluminum alloy is planned to be used for reverse circulation drilling in ice. Three types of drill bits made by steel, tungsten carbide and polycrystalline diamond compact (PDC) are prepared for ice drilling. Wireline coring drill with impregnated diamond drill bit is planned to be used by MPDS to obtain the subglacial bedrock*".

More details about the MPDS will be presented in our coming paper, which is now being prepared. The locations of the domestic and Antarctic test sites are added in revised manuscript. The added sentences are "*The air system was first tested in Zhangjiakou, Hebei Province, China after manufacturing. The testing site is about 200 km away from Beijing*", "*The testing site is only about 50 m away from the drilling site of the Russian-Chinese drilling project in 2023/2024 season. The ice sheet thickness at the drilling site is about 545 m according to the drilling results (Leitchenkov et al., 2024)*".

References

Leitchenkov, G.L., Talalay, P.G., Zhang, N., Abdrakhmanov, I.A., Gong, D., Liu, Y., Li, Y., Sun, Y., Vorobyev, M., Li, B.: First targeted geological sampling beneath the East Antarctic ice sheet: joint Russian-Chinese drilling project. Exploration & Protection of Mineral Resources, Special issue, 75–78, 2024.

3. The structure of the paper is not ideal. For instance, the "components" section includes "principles" as well. I would suggest reorganizing the structure of the paper in a more common way, with an introduction, methods (both air and drilling fluid), results (tests), and conclusions.

The structure of the manuscript was reorganized as the following way: introduction, design of the air system and the DFCS, testing of the air system and the DFCS, experiences and lessons.

In the revised manuscript, the related sentences in the "components" section have been moved to the "principles" section, such as "*The air filter is mainly used to remove impurities in the air, such as oil droplets, water droplets and micro solid particles.*", "*Different types of heat exchangers were considered in the design, including the plate heat exchanger, finned-tube heat exchanger, shell and tube heat exchangers. Compared with finned-tube and shell and tube heat exchangers, the plate heat exchanger is more compact in size and lighter in weight. There are two types of plate heat exchangers, which are the brazed plate heat exchanger and gasket-type plate heat exchanger. The brazed plate heat exchanger is difficult to clean when solid particles accumulate inside. A gasket-*

type plate heat exchanger was selected because it uses a bolt-connected plate for easy disassembly during cleaning".

4. What is targeted area for subglacial drilling? Arctica? Antarctica? The logistics and requirements for the system will vary depending on the potential drill site location.

The targeted area for subglacial bedrock drilling is Antarctica. In the revised manuscript, the word "polar region" is replaced by "Antarctica".

5. The environments of the domestic tests conducted in China and Antarctica differ greatly in terms of temperature and the nature of the drilling material (firn or ice vs sandstone). As a result, these tests cannot provide reliable evidence of the system's performance in polar regions. In addition, a lot of information about field tests, such as the rate of penetration, the volume of recovered chips, the diameter of the drilled borehole, etc. is not included.

It is true that the testing environments in China and Antarctica are quite different. However, it is difficult to create a similar testing environment as the Antarctica in China, so the domestic test is only used for checking the basic function of the drilling equipment. In the revised manuscript, we mentioned "*the testing environment in China is quite different with Antarctica and the domestic testing can only check the basic function of the air system*".

The following sentences are added to provide more information about testing results. "*The upper 42 m of the borehole was drilled by a 178 mm drill bit made by steel. Total 25 days were spent to deepen the hole from surface to 42 m because of many unexpected problems in the drill bit and air the system.*", "*The diameter of the borehole from 31m to 110 m was 102 mm and a production drilling rate was about 8-12m/day*". The volume of recovered chips was not measured in field test and was unknown.

More details are beyond the scope of the manuscript and can be found in our coming paper about the testing result in Antarctica.

6. English language is primitive and, in some places, awkward.

Language of the revised manuscript has been edited by native English speaker.

Comments on the text:

L22. "Polar regions, which mainly include Arctic and Antarctica, …": The term Polar Regions has a more precise definition.

"Polar Regions" was replaced by Antarctica in the revised manuscript. The explanation of the polar region at the beginning of the manuscript has been deleted.

L32, 33. "by USA", "USA drilled" – better US drillers or US scientists.

Changed to "US scientists"

L34. "China retrieved" – Chinese drillers.

Changed to "Chinese drillers retrieved…"

L35. I'd suggest also to mention Chinese-Russian subglacial drilling project: Talalay PG, Leitchenkov G, Lipenkov V., Sun Y, Zhang N, Gong D, Liu Y, Li Y, Sun Y, Abdrakhmanov I, Vorobyev M, Khalimov D, Fan X, Salamatin A, Ekaykin AA, Bing Li B (2025). Rare ice-base temperature measurements in Antarctica reveal a cold base in contrast with predictions. Commun Earth Environ 6, 189. doi.org/10.1038/s43247-025-02127-1

The following sentences has been added to provide more information about Chinese attempt in subglacial bedrock drilling "*In 2018/2019 season, …. Five years later, Chinese-Russian subglacial drilling project recovered a subglacial bedrock core of 0.48 m beneath 541 m ice sheet (Talalay et al., 2025)"*.

References

Talalay, P. G., Leitchenkov, G., Lipenkov, V., Sun, Y., Zhang, N., Gong, D., Liu, Y., Li, Y., Sun, Y., Abdrakhmanov, I., Vorobyev, M., Khalimov, D., Fan, X., Salamatin, A., Ekaykin, A. A., Li, B.: Rare ice-base temperature measurements in Antarctica reveal a cold base in contrast with predictions. Commun. Earth. Environ., 6, 189, https://doi.org/10.1038/s43247-025-02127-1, 2025.

L40. Truffer et al., 1999 used Longyear Super 38 drill rig.

The Longyear Super 38 drill rig was mentioned in revised manuscript.

L45. "it has a greater ability to deal with drilling accidents" – questionable statement.

The sentence was deleted.

L54-55. "it required ambient temperatures below ~10 °C to cool the compressed air to below 0°C" – not clear.

In the reference, it is mentioned that "*However, the temperature of the air leaving the aftercooler is still about 10 ℃, above ambient, so ambient temperatures must be below -10 ℃ or the air will melt the ice chips*."

The sentence was rewritten as "*…it required ambient temperatures below ~10 ℃, or the air will melt the ice chips*".

L62-63. "oil-based drilling liquid" – RAID used ESTISOL™ 140 that is not oil-based fluid.

The word "oil-based" was deleted.

L70-71. The issue of ice hydrofracturing is more complex than it may seem from a brief description in two sentences.

It is true that the ice hydrofracturing is complex. To address this, another sentence was added. "*At present, the occurrence condition of ice hydrofracturing is still not clear and there is no effective way to prevent it from happening*"

L79. "the ice that was leftover" - ??

"the ice that was leftover" was changed to "the ice below".

L83-84. "newly designed" contradicts to "were improved"

The word "were improved" was deleted.

L91. What are "and so on"?

"and so on" was replaced by "size of ice chips and ice sheet temperature"

L96. "In theory, the compressed air should be, at least, cooled to below 0 ℃." Why? To prevent ice melting?

""to prevent ice from melting" was added after "below 0 ℃"

L97. "The dew point of compressed air was expected to be lower than -40 ℃" Why?

The following sentences were added to explain the reason why the dew point of compressed air was expected to be lower than -40 ℃. "*At the dew point of -40 ℃, the water content in the compressed air drops to 0.176 g·m^{-3}, which is considered to be very dry*"

L98. "The air system is required to work at temperature of -30 ℃". It depends on potential drill sites. Where is targeted area for subglacial drilling?

The targeted drilling area of the MPDS has a distance less than 100 kilometers away from Antarctica coast. The following sentence was added. "*The targeted drilling area of the MPDS has a distance* *less than 100 km away from Antarctic coast. In the targeted drilling area, the average atmosphere temperature is usually less than 30℃ (Wang and Hou, 2011). Consequently, the air system is also required to work at temperature of -30 ℃…*"

References

Wang, Y. and Hou, S.: Spatial distribution of 10 m firn temperature in the Antarctic Ice Sheet, Sci. China Earth Sci., 54, 655-666, https://doi.org/10.1007/s11430-010-4066-0, 2011.

L105. Incorrect positioning of Fig. 2 reference. How Fig. 2 can illustrate that "its temperature can rapidly increase as high as 80–100 °C"??

The following sentences were added. "*As shown in Fig. 2, the air system mainly contains a compressor, a receiver, a freezing dryer, a desiccant dyer, a cooler, a cyclone dust collector, three air filters and several sensors (Fig. 2). The compressor is used for generating compressed air from atmosphere.*"

"80–100 °C" is the common situation for most compressors. In the "principle" section, the related data about temperature has been deleted. For example, "*as high as 80–100 ℃*", "*Generally, the hot air can be cooled down to 30–50 ℃ at the outlet of compressor*".

L113. "In time" – better, "during operation'.

Changed.

L126-127. The obvious statement. It's better to delete: "to monitor the flow rate, pressure, temperature, and dew-point of compressed air injected into a borehole".

The sentence was deleted.

L135. "because 10–20 % of air could be lost during the drying and cooling processes at the surface" – some robust estimations should be provided to support these numbers.

According to the manufacturer of the air system. About 8% of compressed air is lost to remove condensed water from the desiccant dyer. The freezing dryer can loss 0.5% of compressed air during water drainage. In addition, the air filters and air receivers also loss some compressed air during water drainage. In total, the lost air is more than 10%. The following sentences were added. "*During drying and cooling processes of compressed air at the surface, about 8% of compressed air is lost to remove condensed water from the desiccant dyer. The freezing dryer can loss approximately 0.5% of compressed air during water drainage. In addition, the air filters and air receivers also loss some* *compressed air. In total, the lost compressed air could be more than 10%. In results, the selected compressor had a flow rate of 12 Nm³/min*".

L151. How much does the air temperature rise in adsorption tower?

According to the manufacturer of desiccant dyer, the air is usually heated to 180–220℃ to dry the moist desiccant. The original sentence was rewritten as "*The absorption tower is externally heated with power of 4.5 kW to heat the compressed air to 180-220℃. And then, the heated compressed air is used to dry the moist desiccant*".

L151-152. "it takes about 15–30 minutes to dry a tower". Is this time enough to dry air with the flow of 10 Nm3·min-1?

Our description made a misunderstanding. According to the manufacturer, 15–30 minutes are required to dry the moist desiccant in one tower. It doesn't mean that 15–30 minutes are required to dry compressed air. The sentence has been changed to "*Generally, it takes about 15–30 minutes to dry the moist desiccant in one absorption tower*".

L153-154. -10 C is also below zero. The concrete temperature range for cooling in the first stage needs to be determined.

In the first stage, the air can be cooled to the temperature of -10–0℃. The sentence has been changed to "*first, to a temperature of -10–0℃, and then to below -10 ℃*".

L160. "air filter precision"?

In table 1, the "filter precision" is replaced by "filtration rating", which is a more common description of air filter precision.

L164. "Left and right" are relative terms that depend on a person's point of view.

It is right. To clearly demonstrate the left and right parts of the air system, the following sentence was added "*In this paper, the left part refers to the half container close to the triangular bracket of the sled, while the right part refers to another half container*".

L198 "did not work" or did not test?

Should be "did not test". It has been changed in revised manuscript.

L199. Fig 8 is cited before Fig. 7.

Fig 8a has been deleted.

L210 and further. Was the temperature measured with precision of ± 0.01 C?

The precision of the temperature sensor used in the air system is ±1℃. In original manuscript, we used average value of measured data with precision of ±0.01℃ to show the testing results. In revised manuscript, the average value only shows the precision of ±1℃. It is worth to be mentioned that the dew-point hygrometer used in air cooler has a ±0.1℃.

L209-220. The description is not very clear. I suggest to modify text or convert it to a table.

The text has been modified to "*The testing results of the air-system from January 12th to 15th, 2025 are shown in Fig.8. The flow rate of compressed air was 9.3–12.4 Nm³·min-1 with an average value of 10.5 Nm³·min-1 (Fig.8a). The average pressure of compressor was kept at 0.7–1 MPa, owing to the pressure loss at the conduit of the surface equipment (freezing dryer, desiccant dryer, air cooler, air hose, swivel, valves etc.) and downhole drill tools (Fig.8b). The air temperature increased to approximately 76–89 ℃ with an average value of 81 ℃ after compressed by the compressor (Fig.8c). After cooling by the built-in air fans in the compressor and the receiver, the compressed air entered the freezing dryer at a temperature of 24–44 ℃ (Fig.8d). However, the freezing dryer did not work well, and the compressed air was cooled only to an average temperature of ~35 ℃, and the compressed air was not dried to the required dew-point of 2–10 ℃ (Fig.8e). In the air cooler, the compressed air was cooled again. In field testing, only one stage of cooling was used. When only the first cooler was used, the air temperature at the its outlet decreased to-17.4–-7.9 ℃ (Fig.8f). However, the temperature of the compressed air increased to -12.4–-4.9℃after flowing through the second cooler (Fig.8g). The reason is that the second cooler did not work and the compressed air was warmed a little by ambient atmosphere in heat exchanger of the cooler. The first cooler was not used after January 14th. When only the second cooler was used for air cooling, the temperature sensor installed at the outlet of the first cooler monitored a temperature variation from 17.6 to 41.7 ℃ (Fig.8h). After cooled by the second cooler, air temperature can decrease to -15.9–-5.1 ℃ (Fig.8i). Regardless of whether the first or second cooler is utilized, the temperature of compresses air was lower than to -4.9 ℃ before injected into the ice borehole. In general, the air cooler can cool the compressed air effectively. As shown in Fig. 8j, the dew-point of the compressed air varied from -11.3 to 19.9 ℃ after dried by the freezing dryer and the desiccant dryer. However, the dew-point of the compressed air was higher than 0 ℃ in most situation, which was significantly below the required dew point of -40℃. The testing results showed the poor* *performance of the freezing dryer and the desiccant dryer. After cooled in the cooler, the dew point of the compressed air decreased to -21.2–4.6 ℃ (Fig. 8k). This implies that some water vapor has been frozen into ice in the cooler. The frozen ice can accumulate in the pipeline of the cooler and then lead to ice plug. That is the reason why the air cooler was broken after January 15th. The detailed data regarding to the testing results can be found in the corresponding supplements Table S1*".

In addition, the original figure 7 was redrawn.

L249. As far as I understand, air cooler was not used in domestic tests.

Air cooler was only tested in China to check its function, just as shown in section "air system performance". However, in this test, the cooled air was not used for drilling. In the domestic tests to drill the underground soil and rock, the air cooler was not used.

L252-254. A relevant reference is needed for this statement.

The following reference was added.

Reference

Bentley, C. R., Koci, B. R., Augustin, L. J.-M., Bolsey, R. J., Green, J. A., Kyne, J. D., Lebar, D. A., Mason, W. P., Shturmakov, A. J., Engelhardt, H. F., Harrison, W. D., Hecht, M. H., Zagorodnov, V. S.: Ice drilling and coring, In: Drilling in extreme environments: penetration and sampling on earth and other planets, edited by Bar-Cohen, Y. and Zacny, K., WILEY-VCH Verlag GmbH & Co., KGaA, Weinheim, Germany,221-308, https://doi.org/10.1002/9783527626625.ch4, 2009

Talalay, P. G. and Pyne A. R.: Geological drilling in McMurdo Dry Valleys and McMurdo Sound, Antarctica: Historical development, Cold Reg. Sci. Technol., 141, 131-162, https://doi.org/10.1016/j.coldregions.2017.06.007, 2017.

L258. It is not report. It is paper or article.

The sentence has been changed to "*The flow rate and pressure required for ice and subglacial bedrock drilling below 1000 m was roughly estimated according to the method of Alemany et al. (2021)*".

L257-258. Refereeing to Alemany et al. (2021) in order to choose flow rate and pressure required for ice and subglacial bedrock drilling is incorrect method because borehole depth, diameters of drill pipes and bits are absolutely different. Authors should provide their own estimation of surface pump requirements.

We only use the method provided by Alemany et al. 2021, instead of choosing the flow rate and pressure according to their results. Our estimation is based on the type of drilling liquid, borehole depth, borehole diameter, and drill-rod size. The details of the estimation are as following.

The flow rate and pressure of drilling liquid required in ice drilling and subglacial bedrock drilling can be calculated according to Alemany and others (2021). In the calculation, the penetration rate is also set as 100 m/h, while the concentration of ice chips is assumed to be 0.025. Kerosene JET-A1 is assumed to be drilling liquid. The drilling fluid are considered to be at the temperature of −30 °C, which has a density of 846 kg/m^3 and a viscosity of 5.29×10^{-6} m^2/s (Talalay and Gundestrup, 2002). The safe factor of pressure is set as 1.5. In both ice drilling and subglacial bedrock drilling, the maximum drilling depth is considered to be 1000 m. It is worth to be mentioned that liquid reverse circulation is used in ice drilling while liquid normal drilling is used in subglacial bedrock drilling.

As shown in the following Fig. S1, the required flow rate keeps constant with increased drilling depth. In our case, the flow rate is about 76 L/min. However, the required liquid pressure during ice drilling increasing linearly with drilling depth increasing. In a 1000 m borehole, the required liquid pressure can be more than 1.0 MPa. The required flow rate and pressure in subglacial bedrock drilling has the same variation trends as in ice drilling. To obtain bedrock sample below 1000 m ice, the required flow rate is less than 70 L/min and the required pressure is about 1.6 MPa. To ensure the ability of the drilling-fluid pump, it is expected to have a rated flow rate of 100 L/min and maximum pressure of the 2 MPa.

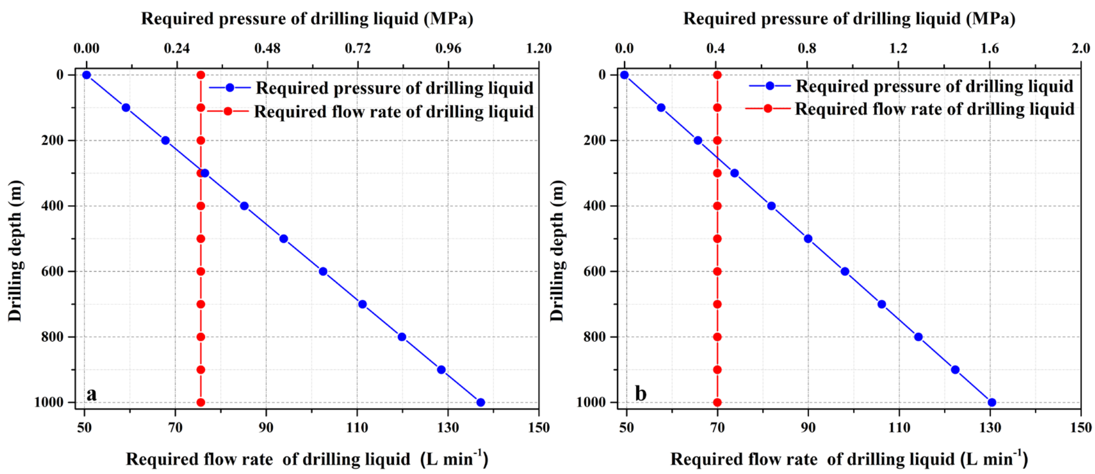

Figure S1. Flow rate and pressure of drilling liquid required in ice drilling (a) and subglacial bedrock drilling (b)

As mentioned above, the estimation of the flow rate and pressure needs the type of drilling liquid, borehole depth, borehole diameter, and drill-rod size. The detailed information will be provided in our coming paper about the whole MPDS, including the calculation process of flow rate and pressure. In the study, we focus on the design and test results of the drilling liquid circulation system, so the estimation is not contained in the manuscript.

L261. Why 2 MPa. Reference?

See the explanation above.

L261-263. A poor comparison. Both the RAID and SUBGLACIOR systems were designed to drill more than 3000 meters.

The comparison with RAID and SUBGLACIOR has been deleted.

L263. “The drilling fluid must be colder than -2 °C in polar regions” – Reference?

Theoretically, the drilling fluid must be colder than 0 °C in polar regions to prevent ice from melting. In our case, -2°C is expected. The following sentence are added. “*The drilling fluid must be colder than 0 °C…. In our case, the temperature of drilling liquid is expected to be lower than -2°C*”.

L271-272. “The drilling liquid need not…” – sentence is not clear.

The sentence was changed to “*The drilling liquid don’t need to be actively cooled…*”.

L333. “Left and right” are relative terms that depend on a person’s point of view.

The following sentence has been added in the revised manuscript. "*In this paper, the left part refers to the half container close to the triangular bracket of the sled, while the right part refers to another half container*".

L386-392. Language problems.

The sentences were reorganized as "*In the field, the flow rate of drilling liquid had to be regulated with a pressure-relief valve by operator. Besides, the circulation pump could not suck the drilling liquid from settling tank to vibration sieve because the liquid level in settling tank was lower than the circulation pump. The ice chips became very hard after being centrifuged. Removal of the hard ice chips from centrifuge drum was difficult and labor-intensive. In addition, there was no brake on the vertical centrifuge and much time was wasted in waiting for it to stop before cleaning it*".

L400-401. What does "vertical centrifuge … with brake and self-cleaning function" mean?

There is a type of vertical centrifuge, which has buit-in brake and can remove the hard ice chips without human. The sentence was changed to "*Fourth, a type of vertical centrifuge with built-in brake should be used and the vertical centrifuge should have the ability to remove the hard ice chips by itself, instead of operator*".

L406-407. Is this conclusion??

The name of the section was changed to "Experiences and lessons".

L 408-409. I disagree with the statement that "the design principle of the air system was proved to be feasible." The system requires significant modifications and additional testing.

The sentence was changed to "The testing results shows that the air system requires significant modifications and additional testing".

L412-413. "For atmospheric temperatures lower than -20 ℃, a passive heat exchanger with a large air fan is strongly recommended for cooling compressed air." This system was neither designed nor tested. Therefore, how can the authors "strongly recommend" it?

The sentence was changed to "*For atmospheric temperatures lower than -20 ℃, the feasibility of cooling compressed air by a passive heat exchanger with an air fan is worthy to be studied*".

L420-421. It seems that the separation system has not worked well. Therefore, the system needs significant modifications and further testing.

The sentence was changed to “*The vibration sieve and the vertical centrifuge required significant modifications to separate ice cuttings from the drilling liquid efficiently*”.

Comments on the figures:

Figure 1. Schematic diagram looks a bit strange without any connections (lines) between subsystems.

The electricity line and the air/drilling liquid pipeline were added to Fig.1.

Figure 4. I suggest deleting one of the 3D models and installing all signs on only one of them.

If we deleted one of the 3D models, it can’t install all signs on only one of them, so both the 3D models should be kept.

Figure 5. It is not informative - I suggest deleting it.

Deleted.

Figure 6. It is not informative - I suggest deleting it.

Deleted.

Figure 7. Commenting on the figure, it would be better to talk about ranges rather than average values.

In the revised manuscript, the data ranges are mentioned. However, the average value still be kept.

Figure 11. I suggest deleting one of the 3D models and installing all signs on only one of them.

If we deleted one of the 3D models, it can’t install all signs on only one of them, so both the 3D models should be kept.

Figure 12. It is not informative - I suggest deleting it.

Deleted.

Figure 13. It is not informative - I suggest deleting it.

Deleted.

Figure 14. Commenting on the figure, it would be better to talk about ranges rather than average values.

In the revised manuscript, the data ranges are mentioned. The test results of the air system also were presented in ranges instead of average values.