Development of an automated pump efficiency measuring system for ozonesonde utilizing an the airbag-type flowmeter

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Abstract. We have developed a system to automatically measure the flow rate characteristics (i.e., the pump efficiency) of the pump, so-called "pump efficiency", under various pressure situations, simulating upper-air conditions. The system consists of a flow measurement unit incorporating a polyethylene airbag, a pressure control unit that reproduces a low-pressure environmental conditions, and a control unit that integrates and controls these elements to enable fully automatic measurement. The Japan Meteorological Agency (JMA) has been operationally measuring the pump efficiency for the Electrochemical Concentration Cell (ECC) ozonesonde using the system since 2009, resulting in a significant body of related data collected and accumulated over a period of twelve years. The long-term stability of the system’s performance has been confirmed, and the long-term measurement data also showed that the pump flow characteristics of ozonesonde differed among production lots. We evaluated the impacts of the variance in these characteristics on the observed ozone concentration data, comparing with the reference ozone profiles. The influences on total ozone estimation were up to approx. 4% to the maximum, the standard deviation per lot was approx. 1%, and the standard deviation among lots was approx. 0.6%.

1 Introduction

Atmospheric Ozone in the atmosphere protects the biosphere by absorbing harmful ultraviolet radiation. In order to monitor the destruction of the ozone layer due to the release of chemical substances caused by human activities, the World Meteorological Organization (WMO) plays a leading role in observing ozone profiles on a global scale to monitor ozone layer deterioration caused by chemical release from human activity (Smit et al., 2021).

Ozonesonde observations are the only means of directly determining the actual vertical distribution of ozone from the troposphere to the lower stratosphere. The ozonesonde model used for such observations is a balloon-borne...
measurement sensor to be flown up from the ground up to a height of around 35 km, at which point the balloon bursts, while taking in the ambient air is taken in and measuring the amount of ozone concentration is by electrochemically measuring electrochemical method. The downlink of the data, through the coupled radiosonde transmission, also provides pressure, temperature, humidity and position measurements. The downlink of the data is taken care of by the radiosonde - also providing pressure, temperature, humidity and position measurements - the ozonesonde is coupled with. Since around 2008-2010 (depending on the station), the Japanese Meteorological Agency (JMA) has been using the Electrochemical Concentration Cell (ECC)-ozonesonde developed by Komhyr (1969, 1971). These units are also widely used in the world, and about 90-95% of stations of WMO / the Global Atmosphere Watch (GAW) programs' ozone observing networks use this type (World Ozone and Ultraviolet Radiation Data Centre, “Dataset Information: OzoneSonde”). Historically, since 1968, JMA began observing the vertical ozone distribution with the KI solution and the Carbon electrode type (KC) - ozonesonde developed at the Agency’s Meteorological Research Institute of JMA (Kobayashi et al., 1966a; Kobayashi and Toyama, 1966b, 1966c; Hirota and Muramatsu, 1986).

An ozone sounding measurement originates from an ozone sensor unit (piston pump, motor, reaction cells, tubes, etc.) and is extended with measuring the measurements taken from the coupled radiosonde unit (pressure sensor, temperature sensor, humidity sensor, GPS antenna, etc.) as shown in Fig 1. The ozone sensor unit has a small piston pump to bubble the ambient air into the reaction cell and measures the electric current generated by the chemical reaction from the potassium iodide solution contained in the cell with the ambient ozone in the sampled ambient air. The ozone concentration is calculated from this electric current. The ozone concentration is calculated from this electric current and the volumetric flow rate of the piston pump.
Figure 1: Appearance of the ozone sensor of the ECC*-type ozonesonde (left) and connected GPS sonde (right).

Figure 2 illustrates shows how the pump operation. Firstly, the ambient air taken into the pump is compressed until its pressure is balanced with the back-pressure associated with the hydraulic head pressure of the reaction cell and a Teflon rod in the reaction cell (1). The compressed air is then discharged to the cell by the force of the piston (2). When the piston is completely pushed in, there is a dead space inside the pump (3), and the compressed air remaining in it expands until it is balanced with the ambient air pressure (4). Then, the piston draws in a fresh sample of ambient air (5). The cycle is repeated for each pump rotation. The steady pump speeds typically range from 2,400 – 2,600 rotations per minute (RPM). During the ozonesonde observation, this cycle is repeated. Hydraulic head pressure, which is the main factor causing back-pressure, can be considered essentially uniform regardless of ambient air pressure. The back pressure could be assumed nearly identical at the ground level pressures and at lower pressures in the upper air, while the latter varies but the ambient air pressure is different along with the altitude. Under these conditions, the air taken in is more compressed in step (1) and the air in the dead space is more expanded in step (4). In other words, as the ambient air pressure decreases, the intake air-volume of air intake (=pump flow rate) into the reaction cell also fully-reduces. Thus, as a consequence, the pump is affected by the ambient air pressure, which governs its efficiency.
Based on laboratory pump flow measurements (Komhyr et al., 1986, 1995; Johnson et al., 2002), Smit and the panel for ASOPOS (2014) and Smit et al. (2021) provide useful tables listing pump flow correction factors and pump flow efficiencies as a function of air pressure. These values are averaged from the experiments at the time of the ECC-ozonesonde development and the values recommended by the manufacturer. Causes of pump flow reduction (dead volume in the pump piston of the pump, pump leakage, hydraulic head pressure of the reaction solution in the reaction cell, etc.) can vary considerably among individual ozonesondes. In order to eliminate such observational uncertainties, it is necessary to accurately determine the pump efficiency of individual ozonesondes in the preflight preparation. However, such determination is not normal practice in ozonesonde launches, as it is considered technically difficult and time-consuming. As a result, most ozonesonde profiles are produced using average pump efficiency curves. Individual pump efficiencies have already been measured by other investigators in the past. For example, the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory (NOAA / CMDL) developed a bubble silicone membrane flowmeter involving the use of oiling silicone oil (Johnson et al., 2002), and showed that the conventionally used standard pump efficiency correction tables (Komhyr et al., 1986, 1995) were underestimated as compared to the pump efficiency correction efficiencies of the currently manufactured ECC-ozonesondes. Also, the University of Wyoming has measured individual pump efficiencies using an airbag evacuation type flowmeter equipped with an airbag and a gear pump with high pump efficiency (Johnson et al., 2002). However, as no pump efficiency measuring systems are currently commercially available, we developed such a system at the Aerological Observatory in Tateno, Japan. After examining various measurement methods, we adopted an airbag method approach.

Figure 2: Explanation of how the piston pump operates during observation, and effect of how the dead space on the pump affects pump efficiency.
In this paper, firstly in section 2, we introduce the outlines of the automated pump efficiency measuring system. In section 3, the measurement method and procedures for the using airbag type system, Section 4 describes are explained. The calculation of pump efficiency calculation, and is described in section 4. Lastly, in Section 5 covers, the statistical results for pump efficiency via as obtained from the operational observation for the current this decade and the long-term stability estimates of the pump measurement system are shown.

2 System Overview of the system

The automated pump efficiency measuring system is roughly divided into three parts: a Control unit, Pressure control unit and Flow measurement unit. Figure 3 outlines shows the conceptual diagram of the system, and Figure 4 shows its actual appearance. The control unit is designed for control of the whole measurement system via a PC with a module that communicates directly with peripheral equipment. The pressure control unit consists of a vacuum pump, a vacuum controller, and a digital barometer. The flow measurement unit consists of an air-bag type flowmeter in a vacuum desiccator that allows various pressure conditions down to 3 hPa.
Figure 3: Schematics of the automated measurement system of the pump efficiency measurement system for the electrochemical concentration cell (ECC) ozonesonde.

The control unit consists of a Windows PC combined with various communication modules (DIO, GPIB, and RS232C) to control the entire system and collect measurement data. As these modules and the control PC are connected via USB, the system can be controlled using a general-purpose PC.

The Windows program to control the system was developed as software running on Windows, and is used to adjust the pressure control unit and the flow measurement unit. The program also enables the function to...
conversion of various measurement data acquired from the flow measurement unit at regular intervals into physical values and collection of the data together with other information such as the digital barometer readings. The pressure control unit controls the air pressure in the vacuum desiccator to reproduce a low-pressure environment. As during balloon ascent, the ozonesondes are not only subjected to decreasing atmospheric pressure, but also to low-temperature conditions (as low as -60 to -80°C) during balloon ascent. For this reason, we initially tried efforts to reproduce not only the low-pressure environment, but also the low-temperature environment both conditions. However, pump efficiency measurements in a low-temperature environment showed that temperature does not exhibit a linear relationship with pump efficiency, and even shows a negligible effect, at least in the temperature range of actual atmospheric conditions. For this reason, we decided to perform measurements by reproducing only with the low-pressure environmental conditions. Since the minimum pressure exhaust limit of the unit is less than 3 hPa, the entire pressure range of ozonesonde measurements can be reproduced.

By manipulating the opening degree of the exhaust valve opening in the vacuum controller with the control program, the pumping speed of the vacuum pump, (equating to the rate of the decompression speed in the desiccator), can be adjusted. The pressurization rate can also be controlled by opening and closing the solenoid valve for atmospheric pressure release.

With these adjustment functions, the air pressure in the desiccator can be maintained to within approximately ± 0.1 hPa of the target air pressure by setting the decompression rate to zero during the flow measurement performed at each specified air pressure. At the start of depressurization and pressurization, a series of procedures is followed to prevent sudden air pressure changes in the desiccator, which might cause a backflow of oil from the vacuum pump to the desiccator. The control program allows safe execution of these steps.

The flow measurement unit consists of a vacuum desiccator, a flowmeter controller, and a control PC. Figure 5 shows the schematic diagram of the flow measurement unit.
The flowmeter controller, which is set outside the vacuum desiccator, controls the flowmeter and acquires flow values of them. The flowmeter controller supplies power to the flowmeter, allows monitoring and controls of the flowmeter status every millisecond using the built-in microcomputer (H8/3052F), and enables sends and receives issuance/receipt of control commands and transfer of measurement data to the control PC using RS232C. This allows real-time measurement control on a millisecond scale, thereby significantly reducing the load of the control PC.

The airbag type flowmeter has a conversion board to adapt the output of various sensors to the input of a small computer board, and a switch board to control the power supply of the pump and solenoid valve. These power supply lines and signal lines are electrically isolated using photo couplers to reduce noise contamination of the signal lines. Figure 6 shows the piping connection diagram of the airbag type flowmeter. The inflation and deflation valves are fluoreoresin three-way solenoid valves, with NO (normally open) to COM (common) communication when not powered, and NC (normally closed) to COM communication when powered, and are switched among these valves alternately, to pump air in and out of the airbag.
Figure 6: A piping connection diagram of airbag type flowmeter. The bag is made of polyethylene. The bag is made of polyethylene in a volume of 140 ml. The inflation and deflation of the bag is conducted by using two magnet valves. The pressure between the inside and outside of the bag is measured with a differential pressure gauge. Temperatures in the bag and pump are measured by thermometers. The revolving speed of the pump is measured by an optical instrument. The airbag is equipped with a port for differential pressure measurement separately from the intake and exhaust ports to ensure stable differential pressure measurement. A Model 265 Setra Systems pressure transducer, Model 265, is used as a micro differential pressure gauge with a measurement range of ±1 hPa and an accuracy of ±1 %FS. The material of the airbag must be able to deform with very weak forces, be airtight, and have little stretch and shrinkage, and should be easy to work with and manipulate. Among the available materials, polyethylene film with a thickness of 0.01 mm demonstrated the best optimal behaviour. In addition, wrinkles caused by uneven deformation as the airbag repeatedly expands and contracts can cause erroneous measurements, so a smaller fluoroplastic film is placed inside the bag to prevent these. After as a result of repeated prototyping, the airbag with an essentially took on a shape similar to that of an intravenous drip bag was adopted.

The main control and measurement features of the flow measurement unit are as follows:

- Pump ON / OFF control
- Control of flow path switching via valves
- Measurement of differential pressure difference between inside and outside of the airbag (0.01 hPa)
- Measurement of pump, desiccator and airbag temperatures (0.1°C)
Measurement of pump motor speed with a handmade digital tachometer attached to the ozone sensor (0.1 rpm). The tachometer shines light on the rotating part of the pump and detects the reflection light to determine the number of revolutions. The rotating part is partially covered with a non-reflective black sticker. When light hits the sticker, the light is not reflected, indicating the tachometer can measure a full revolution.

Time interval measurement triggered by the specified differential pressure (1msec)

3 Method for measuring pump efficiency using the airbag method

3.1 Concept and Basic idea

The concept idea of estimating the pump flow rate (pumping power) using an airbag involves timing to measure the inflation time from the least to the most deflated state of the bag to the most inflated state, and the deflation time from the most inflated to the most deflated state. Assumming the airbag internal volume of \( V_{\text{airbag}} \) when the most inflated/deflated states are assumed to be constant regardless of ambient pressure, as long as internal/external pressure are equal to be constant regardless of ambient pressure, the pump flow rate \( S(p) \) at a given pressure \( p \) can be estimated with the averaged inflation and deflation time \( t(p) \) as

\[
S(p) = \frac{V_{\text{airbag}}}{t(p)}.
\]  

The pump efficiency \( k(p) \) at the given pressure \( p \), which is defined as the ratio of the pump flow rate to that estimated at the ground-level pressure \( p_0 \), can be calculated as follows:

\[
k(p) = \frac{S(p)/S(p_0)}{(V_{\text{airbag}}/t(p))/(V_{\text{airbag}}/t(p_0))} = \frac{t(p_0)}{t(p)}.
\]  

As this equation shows, we do not need to know the exact volume of the airbag does not need to be known.

Meanwhile, on the other hand, it is necessary to assess whether or not the airbag is fully inflated or deflated, which is done by evaluating its internal/external pressure in some way. Therefore, we use the differential pressure between the airbag's inside and outside. The differential pressure threshold was set to +/- 0.8 kPa (+: inflation; -: deflation) during inflation and deflation. We will come back to this choice as discussed later in this paper. The flow will be switched using two valves shown in Fig. 6 when the differential pressure reaches the thresholds. Figure 7 shows the differential pressure with elapsed time, starting from the time of the maximum deflation. A series of measurements was made when the flow was switched at the ground-level pressure. Plotting of differential pressure during deflation from around the time of maximum inflation (red line) shows that the inflation and deflation times are equal, since they match at the time of maximum deflation. In addition, since the pump flow rate at ground level was stable, the elapsed time can be considered associated with the internal volume of the airbag. These results indicate that differential pressure values during inflation and deflation each represent a certain airbag volume. From the above, pump efficiency can be determined from equation (2) by measuring the time interval at which a certain differential pressure is observed. Since the pump flow rate at the ground level is stable, we can...
consider the elapsed time to be equivalent to the internal volume of the airbag. During inflation and deflation, there seems to be a hysteresis effect (blue line) in which the relationship between the differential pressure and the content volume does not match, but when it is plotted folded around the time of maximum deflation (red line), it matches. This indicates that the inflation time and deflation time are equal, and the pump repeatedly takes in and exhausts a constant volume. We have performed multiple measurements on this and have confirmed that the folded and plotted differential pressure diagrams are always the same. From the above, thus, we conclude that the differential pressure during inflation and deflation each represent a certain airbag volume, and can determine the pump efficiency from equation (2) by measuring the time interval at which a certain differential pressure (hereinafter referred to as the differential pressure threshold) is detected.

Figure 7: Schematics of pressure differences between the inside and outside of the bag as a function of lapsed time. The blue line represents plots of four-time average difference pressure values with and the bag inflation/deflation of the bag is changed when the magnitude of difference pressure reaches 0.8 hPa. The red line shows a symmetric reference line of deflation to the maximum inflation at an elapsed time of approx. around 36 seconds. On/off lines for inflation and deflation are plotted at the top of the upper part of the panel.

The pump correction factor (the reciprocal of the pump efficiency) is obtained only from the time required for airbag inflation and deflation, and in the case of differential pressure $\Delta p$ is expressed from equation (2) as follows:

$$pcf_0(p, \Delta p) = \frac{1}{k(p)} \frac{(p_{\Delta p})}{(p_{\Delta p})}$$  \hspace{1cm} (3)
where \( pcf_\Delta p(p, \Delta p) \) is the pump correction factor for differential pressure \( \Delta p \) at air pressure \( p \) and \( t(p, \Delta p) \) is the time required to reach differential pressure \( \Delta p \) at air pressure \( p \). \( \Delta p \) is the ground-level pressure. In practice, however, the effects of differences in differential pressure thresholds and temperature changes due to the heat generated by solenoid valves and pump motors can cause measurement errors, giving rise to a need for us to consider a correction method.

The details are described in section 4.

### 3.2 Measurement sequence and measured value

In the series of measurements, the automated pump efficiency measuring system recorded values for measurements at pressure levels: the ground-level pressure (six times) and at, 500, 200, 100, 50, 30, 20, 10, 7, 5, 4, and 3 hPa (four times each). Measurements from inflation to deflation are performed 6 times at the ground-level pressure and 4 times at other pressures. In each case, as the first record was at time in the "break-in" of the airbag at each atmospheric pressure, so the values from after the second time onward were taken as the actual measurements—measured values. The final pump correction factor was finally calculated from a factor as the average value of those values observed at the time of inflation and deflation. For each measurement, the system also acquired additional data on the time required for bag's internal/external differential pressure inside and outside the airbag to reach ±0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 hPa (+inflation; -deflation); during inflation, -deflation), pump temperature, and bag internal temperature in the bag. After the cycle of measurements at the different pressure levels, six measurements at ground pressure were made again to check the confirm reproducibility of the pump operation. The measurement pressure, the number of measurements, the differential pressure threshold, and other settings for this sequence of measurements can be changed in the control program.

### 3.3 Consideration of the back-pressure (load) effect

The ECC-ozonesonde has a Teflon rod protruding from the bottom of the reaction cathode cell allowing in order to guide the intake tube from the pump to be guided appropriately properly into the reaction solution, by sliding into the tubing over the Teflon rod, which The Teflon rod could narrow the air flow and produce give pressure resistance. Additionally, in actual ozonesonde observations, the reaction cells are filled with a solution. As Under these situations, the back-pressure necessarily must affect the pump efficiency with these conditions Therefore, at the first step, we investigated the back-pressure effect of the guiding Teflon rod and the reaction solution on the pump efficiency was examined. In all measurement tests, we used the same ECC-type (EN-SCI 1Z) sensor. This section describes the outcome of the survey.

Figure 8 (a) shows the results of a comparison between the cases in which the pump is directly connected to the flowmeter from the exhaust port of the pump and in which the case where the air flows through an empty reaction cell. The experiment showed that the pump efficiency decreased (up to approx about 6% to the maximum at 3 hPa) within connection through the cell, and that the cell itself generated back-pressure, possibly. This back pressure generation may be due to the presence of the Teflon rod’s line.
Next, we examined the relationship between the volume of the reaction solution and back-pressure was also examined. However, if the pump efficiency is measured with an in-cell airbag-type flowmeter will fail due to backflow caused by boiling of the solution during flow observation measurement especially under low-pressure conditions. Accordingly, we used silicon oil with almost the same specific density as the reaction solution was used instead.

Figure 8 (b) shows the results of a comparison between an empty reaction cell and one with 3 ml of an ECC-type standard reaction solution volume of 3 ml. From this result, we found that the load caused by the reaction solution also reduced the pump efficiency (up to approx. about 4% to the maximum at 3 hPa). We considered that the reaction solution's head pressure of the reaction solution causes is considered to have produced this effect.

Figure 8 (c) shows the results of a comparison of pump efficiencies during inflation and deflation under the same load conditions. Normally, the intake speed and exhaust speed of the pump are the same, and the pump efficiency should be the same at the time of intake and exhaust, but the pump efficiency during deflation is always lower than that during inflation (about 8% to the maximum at 3hPa). Since the pump efficiency shows a change tendency depending on the ambient air pressure like the change due to other loads, we consider that an additional load, presumably the dead space of the pump (as explained in section 1), is responsible for it.
コメントの追加 [諸藤42]: Replaced according to Referee#3’s comment “Lines 220-223: I’m not sure that these remarks, or Figure 8c, add anything to the paper. Figure 8c is not mentioned further. The remarks are also confusing, coming in the middle of a discussion about “real-world” back pressures. I suggest dropping these lines, and Figure 8c.”

コメントの追加 [諸藤43]: Larger character size in legends according to Referee#1’s comment “Larger character size in legends”.
From the above discussion in the previous paragraph, we conclude outcomes indicate that a filled reaction cathode cell generates a back-pressure, thereby affecting the pump efficiency, as in real atmospheric conditions. The results in Fig. 9 reveals investigation results showing the correlation of the back-pressure versus ground-level pressure and solution volume in the cell at the ground-level pressure. According to this, the back-pressure is approx. about 3 hPa for the standard ECC-type reaction solution volume of 3 ml. To reproduce this load, the length and diameter of the piping were adjusted, and a load of 3 hPa was successfully applied to the exhaust side without adding any reaction solution into the cell. All further pump correction factors reported in chapters 4 and 5 are always measured and determined with a 3 ml reaction solution in the cathode cell.

Figure 8: (a) Ratio of pump efficiency with direct connection directly to the flowmeter from the pump exhaust port and through an empty reaction cell. (b) Ratio of pump efficiency between the case of an empty reaction cell and one with the standard the case of adding 3 ml of ECC type reaction solution, which is the standard amount of ECC type reaction solution. (c) Ratio of pump efficiency during inflation and deflation under the same load conditions. Inf: Inflation; Def: Deflation; BP0: Back-pressure 0hPa; 0ml: no reaction solution; 3ml: 3 ml of reaction solution.
As discussed above in the previous section, a number of factors can cause various observation errors in pump efficiency measurements. In this section, we explain the correction method to remove those errors.

4.1 Correction for the effects of in-pump heat generation in the pump

The study’s series of pump efficiency measurements began with the ground-level pressure and continued with lower pressure values. As the pump motor gradually heated up due to friction, the exhaled air exhaled (pushed sucked out) from the pump became warmer in the later stages of the measurement. The volume changes caused by the heating of the inflowing air caused a source of errors requiring correction in the measurement results, and should therefore be corrected for. Since the heat capacity of the air discharged from the pump is relatively small, it was assumed that the air was warmed to the same temperature as the pump temperature while passing through the pump, and the initial pump correction factor $pcf_0(p, \Delta p)$ was adjusted as follows,

$$pcf_1(p, \Delta p) = pcf_0(p, \Delta p) \frac{T_{pump}(p, \Delta p=0.8)}{T_{pump}(p, \Delta p=0.8)}.$$  

where $T_{pump}(p, \Delta p)$ is the pump temperature (K) at differential pressure $\Delta p$ with air pressure $p$ ($p_0$ is the ground-level pressure). These are the values at when the differential pressure of 0.8 hPa (at the most inflated state). Table 1 shows the averaged pump temperature during pump efficiency measurements performed by JMA from

Figure 9: Exhaust side load with a reaction cell. 3 ml of the standard reaction solution is equivalent to a load of approx. about 3 hPa.
2009 to 2022. Measurements started after 30 minutes of warm-up measurements, and the pump temperature typically increased by 5-6 °C as the measurement progressed.

Table 1: Pump temperature measurement results for in Sapporo, Tateno, and Naha from 2009 to 2022.

<table>
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<th>Pressure (hPa)</th>
<th>Pump Temperature (℃) [JMA 2009 - 2022]</th>
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</thead>
<tbody>
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<td>3</td>
<td>37.0 ± 2.2</td>
</tr>
<tr>
<td>4</td>
<td>36.7 ± 2.2</td>
</tr>
<tr>
<td>5</td>
<td>36.4 ± 2.2</td>
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<tr>
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<td>31.1 ± 2.0</td>
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</tbody>
</table>

4.2 Correction for the effect of differential pressure effects

The measurement time is defined as the time required for the pump to exhaust all the air and inflate the airbag from zero volume to \( V_{\text{airbag}} \) or to deflate it from \( V_{\text{airbag}} \) to zero similarly under atmospheric pressure \( p \). However, the air actually pumped into the airbag is actually further inflated or deflated by the amount in relation to the differential pressure \( \Delta p \) in addition to the ambient air pressure \( p \). By measuring the differential pressure, thus enabling us to determine of whether the bag is full or empty and detect the bag content and internal volume of the airbag. There is a need to we should consider the effects of this on the measurement time by converting the air pressure change inside the airbag into a volume change. Assuming no change in temperature, using the Boyle-Charles law (assuming no change in temperature), the internal volume of the airbag, \( V_{\text{airbag}} \), changes with the ratio of the airbag differential pressure \( \Delta p \), to the ambient air pressure \( p \). Accordingly, the measurement time \( t_m \) for the net measurement time \( t(p) \), at the air pressure \( p \) is expressed as

\[
t_m = t(p) \cdot (1 + \Delta p/p). \tag{5}
\]
Here, from this equation, it can be seen that the lower the ambient pressure \( p \) is, the values produce a larger the effect on the measurement time. To check the effects of this operational correction (hereafter referred to here as the pressure correction) using \( t_m \) as the measurement time, we varied the differential pressure threshold was varied from \( \pm 0.1 \) to \( \pm 0.8 \) hPa in turn, obtained the pump efficiency with this correction was determined for each pressure, and comparisoned to values with that without the correction was performed. Figure 10 shows the results of comparison results at an ambient pressure of 3 hPa. It can be seen that the pressure correction is generally does a good job effective, but, even after applying this correction, the correlation between the pump correction factor and the differential pressure threshold remains high. 

We consider the effects of the differential pressure can therefore be seen acting as another pump loading factor on the pump. In other words, thus, if the differential pressure acts as an the exhaust (intake) side load when the airbag is inflated (deflated), it is consistent with the results can be seen as consistent with those of the previous pressure correction. However, deriving correction for this effect is not straightforward, as because these loads change during measurement and each different pumps responds differently to these loads. To avoid such effects, we should make measurements at even lower differential pressure thresholds should be considered to avoid such effects, but there is a limitation to the differential pressure thresholds that can be set, very low small differential pressures are outside the detection limit of the micro differential pressure gauge and the measurement of time interval measurements is prone to errors. However, on the other hand, since the pump correction factor without differential pressure correction shows a very high correlation with the differential pressure threshold, we can fully use the y-intercept of the regression line can be comprehensively used as an estimate of the pump correction factor for a zero differential pressure threshold. Accordingly, therefore, in the actual measurement, we estimate the pump correction factor corrected for the effects of the differential pressure in actual measurement can be estimated by from the regression line obtained from the measurement time taken at each of the multiple differential pressure thresholds. The pump correction factor \( pcf_2(p) \) at zero differential pressure with this obtained by the method described above approach is expressed as

\[
pcf_2(p) = pcf_1(p, \Delta p = 0).
\]
Figure 10: Pump correction factors calculated for various different differential pressure thresholds. Values of the pump correction factors (representing the inverse of pump efficiency) calculated for each differential pressure threshold are plotted with and without pressure correction. The values in (a) and (b) are based on the measurement time during expansion and contraction, respectively, at 3 hPa ambient air pressure. These values were measured by connecting as determined with the pump’s inlet and exhaust ports directly connected to a flowmeter.

4.3 Correction for temperature

As the polyethylene of the bag used for differential pressure measurement is made of polyethylene, since polyethylene has the property of expanding and contracting with the change in temperature, we need to consider the changes in bag volume during measurement. If the temperature inside the airbag gradually rises during measurement because the piping leading to the airbag is heated by the heat of the solenoid valve and the circuit board inside the flowmeter housing, and the air pumped into the airbag is heated by the frictional heat of the pump, the temperature eventually rises by around 5 to 10°C in a measurement sequence. Since related this variation in airbag volume is also cause a measurement error, the pump efficiency is corrected using temperature data obtained from thermistors placed near the airbag.

After measuring the pump efficiency while changing the airbag internal temperature inside the airbag variations in a thermostatic bath, it was found that approximately halving of the temperature change rate affected the pump correction factor. It has been confirmed that Charles’ law also is obeyed when the ambient temperature was changed using the same experimental apparatus. This is attributed largely due to the effects of the changes in airbag elongation and elasticity due to the thermal properties of the polyethylene film offsetting the effects of the volume change relating to Charles’ law by around 50%. The based on the results of this experimental results indicated, that the pump correction factor after correction for the temperature-dependent changes in airbag capacity can be expressed as follows.

\[ pcf_2(p) = pcf_2(p_0) \left( 1 - 0.5 \frac{T_{airbag}(p_0, \Delta p=0.8) - T_{airbag}(P, \Delta p=0.8)}{T_{airbag}(P, \Delta p=0.8)} \right) \]  

(7)

where \( T_{airbag}(p, \Delta p) \) is the airbag temperature of the airbag (K) at differential pressure \( \Delta p \) with air pressure \( p \) (Pa is the ground-level pressure).

4.4 Application of pump efficiency measurement results to ozone partial pressure calculation

The pump efficiency \( k(p) \) at atmospheric pressure \( p \) is given by the following equation (Kobayashi and Toyama, 1966).

\[ k(p) = 1 - K \cdot \left( \frac{1}{p} - \frac{1}{p_0} \right) \]  

(8)

where \( p_0 \) is the ground-level pressure (hPa) and \( K \) is a constant. According to Steinbrecht et al. (1998), when adiabatic change occurs in the pump, a power term (specific heat ratio \( \gamma \approx 1.4 \)) should be added to the second term on the right side as follows.
\[ k(p) = 1 - K \cdot \left( \frac{1}{p} - \frac{1}{p_0} \right)^\gamma. \]  

Assuming that this is actually in reality it is a polytropic change relating to because of the effects of heat exchange with the pump in addition to the adiabatic change, the following approximate equation can be given is given. From above, the following approximate expression is given as

\[ pcf(p) = \frac{1}{k(p)} = \frac{1}{1 - K \left( \frac{1}{p} - \frac{1}{p_0} \right)^\gamma} \quad \text{where } \frac{1}{n} \text{ is the polytropic index depending on the ozone sensor, } c_0 \text{ is a constant depending on the ozone sensor and } c_1. \]

\[ pcf(p) = \frac{1}{1 - c_0 \left( \frac{1}{p} - \frac{1}{p_0} \right)} \quad \text{108)} \]

where \( n \) is the polytropic index depending on the ozone sensor, \( c_0 \) is a constant depending on the ozone sensor and \( c_1 \) is \( \frac{1}{n} \).

The application of the pump efficiency measurement results to the ozonesonde observations is based on \( pcf_3(p) \) with the corrections described in Section 4.3. \( pcf_3(p) \) is calculated from the average of three measurements in total, 3 times for each of during inflation and deflation at each specified atmospheric pressure of 200 hPa or less. Using this equation, \( c_0 \) and \( c_1 \) in of the approximate expression equation (108) are obtained by fitting. The pump correction factor \( pcf(p) \) at pressure \( p \) is then calculated from the same approximate equation (108) using the obtained constants \( c_0 \) and \( c_1 \). Note that we do not use ground pressure data are not used because \( pcf_3(p_0) \) should be 1.

5 Data from Pump efficiency data operationally obtained by the JMA’s automated pump efficiency measuring system

Since 2009, JMA has comprehensively evaluated been conducting a complete inspection of EN-SCI ECC ozone sensor’s pump efficiency using with the automated pump efficiency measurement system, and has been using the pump correction factors calculated from the measurement results are used to correct the ozonesonde observations from the Sapporo, Tateno, and Naha stations. This section presents the results of these measurements made over this last 13 years.

5.1 Comparison of pump correction factor2 between JMA and other organizations

Figure 11 shows the results of pump correction factor measurements at Sapporo, Tateno, and Naha from 2009 to 2022 using sensors with similar serial numbers had been used at each station. The values pump correction factors were generally consistent among the stations, although the difference was with slightly larger differences at 3 hPa, where the measurement accuracy is lower.
Figure 11: Pump efficiency measurement for results in Sapporo and Naha from 2009 to 2018, and Tateno from 2009 to 2022. The error bars in the left figure represent the one-sigma standard deviation. All the results measured at 3 sites show close correspondence and are almost synchronized.

Figure 12 shows the results comparing the average pump correction factors for the same pump type (EN-SCI ECC) obtained by other organizations with the representative measured data of typical JMA data. The pump motor specifications were different changed from those of the ozone sensor (serial number after ~24000, serial number, or later) ozone sensors delivered to JMA in 2013. The results indicate that a result, air pressure dependence was seen in terms of the motor speed, and suggest that speed the stability of the speed was not good was unstable depending on the among production lots. We thought that the effect was affecting the pump efficiency. Accordingly therefore, as the results of sensors with serial number 24000 and above are used to calculate the representative data of JMA. For the evaluation of past observation data, we show also the statistical values before the serial number before ~24000 values are shown in Table 2. The standard deviation is larger for sensors after this serial number. Stauffer et al. (2020a) also reported the discovery of an apparent instrument artifact that has caused a fall in total ozone measurements from around a third of global stations to drop starting in 2014–2016, limiting their suitability for calculating ozone trend. Stauffer et al. (2020b) also noted a falloff in total column ozone in various En-SCI ozonesonde sites around serial number 25250.
The measurements were conducted by the University of Wyoming and NOAA/CMDL has made measurements with exhaust-side loading using non-evaporative oil instead of to replace the reaction solution. (Johnson et al., 2002). We replicated this work that with longer extra tubing length to create a simulated back-pressure from of the 3ml of the reaction solution with 3ml reaction solution. According to these comparisons, indicated that the pump correction factors for the period during expansion were close to those obtained by other organizations, and that the tendency in relation to the ambient air pressure was also similar. These outcomes suggest the effectiveness of the proposed newly developed measurement system is working well.

These measured pump flow efficiencies significantly differ from those reported by Komhyr et al. (1995). This is because, as noted by Smit et al. (2021), pump efficiencies in the values of Komhyr et al. (1995) in fact represent an overall correction that includes both the pump flow efficiency and an estimated stoichiometry increase over the period of flight.

Comment [KIm60]: Replaced according to Referee#2’s comment
“Lines 335-336: It appears that “reaction solution” is being used for referring to more than one thing. It is used early in the paper when referring to the actual sensor solution (the KI salt water solution) and then in line 335 it looks like in this text “reaction solution” is referring to head pressure simulation of the sensor solution for NOAA/CMDL pump efficiency measurements, when NOAA/CMDL actually used non-evaporative oil to replace the reaction solution. Then in Line 336, I believe JMA is using extra tubing length to create a simulated back pressure of the 3cc of reaction solution. It would be helpful to be clear where “reaction solution” is actually back pressure or simulated head pressure of the 3cc of reaction solution.”.

Comment [KIm61]: Replaced according to Referee#2’s comment
“Lines 335-336: It appears that “reaction solution” is being used for referring to more than one thing. It is used early in the paper when referring to the actual sensor solution (the KI salt water solution) and then in line 335 it looks like in this text “reaction solution” is referring to head pressure simulation of the sensor solution for NOAA/CMDL pump efficiency measurements, when NOAA/CMDL actually used non-evaporative oil to replace the reaction solution. Then in Line 336, I believe JMA is using extra tubing length to create a simulated back pressure of the 3cc of reaction solution. It would be helpful to be clear where “reaction solution” is actually back pressure or simulated head pressure of the 3cc of reaction solution.”.

Comment [KIm62]: Replaced according to Referee#2’s comment
“Replace “UMYO 2002” with “UWYO 2002” within the graph for Univ of Wyoming (blue line).” and Roeland Van Malderen’s comment.
Figure 12: Comparison of pump correction factors from JMA’s by our airbag method with those from other experiments. Curves of pump correction factors as a function of pressure are represented for the standard Komhyr et al. (1995) line with squares, and JMA pump correction factors are represented marked by the pink line with circles. The error bars represent the one-sigma standard deviation. Also, a curve using the NOAA/CMDL average oil bubble flowmeter values are shown marked by the green line with triangles, and those from that using the Wyoming bag method are shown marked by the blue line with rhombuses (Johnson et al., 2002).

Table 2: The averaged JMA pump correction factors measured by JMA for pre and the sensor serial numbers after post 24000, sensor serial numbers before 24000, and for the entire time period (2009 - 2022).

<table>
<thead>
<tr>
<th>Pressure (hPa)</th>
<th>Serial # $\geq$ 24000 (821 samples)</th>
<th>Serial # &lt; 24000 (566 samples)</th>
<th>ALL (1387 samples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.381 ± 0.047</td>
<td>1.330 ± 0.037</td>
<td>1.361 ± 0.050</td>
</tr>
<tr>
<td>4</td>
<td>1.307 ± 0.040</td>
<td>1.260 ± 0.026</td>
<td>1.288 ± 0.042</td>
</tr>
<tr>
<td>5</td>
<td>1.254 ± 0.034</td>
<td>1.216 ± 0.022</td>
<td>1.239 ± 0.035</td>
</tr>
<tr>
<td>7</td>
<td>1.191 ± 0.028</td>
<td>1.164 ± 0.018</td>
<td>1.180 ± 0.028</td>
</tr>
<tr>
<td>10</td>
<td>1.140 ± 0.023</td>
<td>1.122 ± 0.016</td>
<td>1.133 ± 0.022</td>
</tr>
<tr>
<td>20</td>
<td>1.078 ± 0.017</td>
<td>1.072 ± 0.013</td>
<td>1.076 ± 0.016</td>
</tr>
<tr>
<td>30</td>
<td>1.056 ± 0.015</td>
<td>1.054 ± 0.011</td>
<td>1.055 ± 0.014</td>
</tr>
<tr>
<td>50</td>
<td>1.038 ± 0.013</td>
<td>1.038 ± 0.009</td>
<td>1.038 ± 0.011</td>
</tr>
<tr>
<td>100</td>
<td>1.021 ± 0.010</td>
<td>1.024 ± 0.007</td>
<td>1.022 ± 0.009</td>
</tr>
<tr>
<td>200</td>
<td>1.011 ± 0.008</td>
<td>1.014 ± 0.005</td>
<td>1.012 ± 0.007</td>
</tr>
</tbody>
</table>
5.2 Long-term system stability of the system

We have investigated the long-term stability of the measurement system by evaluating results of multiple measurements on a sample data collected from four pumps investigated at the Aerological Observatory in Tateno from 2010 to 2021. In addition to the correction outlined in Section 4, for this experiment only, we have corrected the pump correction factors in the experiment were adjusted in line with the pump motor speed as shown in the following formula in order to eliminate factor biases between the pump correction factors between the different uses of the same pump using:

\[ pcf_{corr}(p) = pcf(p) \frac{MS(p_0)}{MS(p)} \] (11)

where \( pcf_{corr}(p) \) is the pump correction factor after motor speed correction at atmospheric pressure \( p \), \( pcf(p) \) is the same pump correction factor before motor speed correction at atmospheric pressure \( p \) and \( MS(p) \) is the motor speed at atmospheric pressure \( p \) (\( p_0 \) is the ground-level pressure). Figure 13 shows these multiple pump flow correction factors for the four sample of 4 pumps exhibit. As can be seen, there is no increasing nor decreasing trend in the pump correction factors for neither of the pumps, although individual differences are seen. This demonstrates the long-term stability of the measurement system and freedom from the absence of any aging degradation effect.

Figure 13: Pump correction factors at 10 hPa determined with measured by the same four sensors during the period from 2010 to 2021. Four sensors were used for the measurements.

5.3 Decadal monitoring of individual pump efficiency

Figure 14 shows the time-series representation of individual pump correction factors at 50, 20, and 10 hPa as recorded at Sapporo, Tateno, and Naha stations from 2009 to 2022 (Sapporo and Naha terminated their ozonesonde observations in February 2018). At all stations, the pump correction factor exhibits temporal changes with time, showing a slightly increasing trend although with different slopes. The slope is larger with lower ambient pressure values to around...
As the pump efficiency measurement system turned out to be very stable (Section 5.2), these trends of the pump correction factors should be ascribed to the ozonesonde pumps themselves.
correction factors at 10 hPa are averaged for bins of 1000 of the serial numbers. It can be seen that the variability of the pump correction factors within each production lot is rather modest (1.8%), and that differences between different production lots are mostly statistically insignificant.
コメントの追加 [諸藤65]: Replaced according to Referee#3’s comment
“Figure 15 (upper) appears to be wrongly labelled on the x-axis.”.
Figure 15: Top: Pump correction factors at 10 hPa from measured during 2009 to 2022, sorted by ozone sensor serial number. Bottom: The same pump correction factor at 10 hPa averaged for each bin of 1000 of ozonesonde serial numbers measured during the period 2009 - 2022. The error bars represent the one standard deviation.

Figure 16 shows a comparison of the measured values of the pump flow rate, motor speed, and pump stroke obtained by dividing the flow rate value by the motor speed value at the ground-level pressure and 10 hPa. Although there is no significant change in the measured flow rate, the pump motor speed increased by about 5 to 10% and the pump stroke decreased by the same 5 to 10% after the sensor serial number 24000. This indicates we infer that a shortened pump stroke might increase the relative volumetric ratio of the pump dead space to the piston volume due to different motor specifications after the serial number 24000 (as described in Section 5.1), which may be the origin of a worse deteriorating factor in pump efficiency. Furthermore, focusing on the deviations between the ground-level pressure and 10 hPa measurements, there is little change in the motor speed differences, but with a visible trend in the pump flow rate and pump stroke differences. From this, it is considered that the difference in pump flow rate changes between the ground and the lower pressure values, that is, the difference in measurement time changes, resulting in an increased pump correction factor. In all cases, the motor characteristics fluctuate discontinuously after the serial number 24000, and the
flow rate and other characteristics of the ozone sensor change with each group of sensor serial numbers. Accordingly, we consider that the increasing trend of the pump correction factor is largely attributed to the sensor side.
コメントの追加 [諸藤66]: Larger charachterize of axis according to Referee1’s comment “Larger characterize of axis”
5.4 Influence on the estimation of ozone concentration

This subsection discusses the effects of the variability caused by the changes in the characteristics of the pump flow rate introduced so far on the observed data of total ozone. Fig. 17 shows the impacts on the total ozone integrated values if the table values of the pump correction factors measured by JMA for the ozone sensor serial numbers before 24000 were used instead of using the rather than measured individual pump efficiency correction values. The effects were calculated using the JMA average ozone partial pressure values for the period from 1994 to 2008, which is a typical mid-latitude profile. The ozone partial pressure obtained using the table values for the pump efficiency correction were obtained by dividing the average partial pressure value by the measured pump correction factor and then multiplying the result by the table value. Each of these ozone partial pressure values at each pressure level (the ground-level pressure, 500, 200, 100, 50, 30, 20, 10, 7, and 5 hPa) was integrated to determine the total ozone integrated value, and the relative difference was determined for each of the pump efficiency measurements during the period from 2009 to 2022. Fig. 17 shows the relative differences of total ozone integrated values to the average that value. The total ozone integrated values are determined using the ozone partial pressure values obtained by multiplying the pump correction factor measured during the period from 2009 to 2022 for each pressure levels (the ground-level pressure, 500, 200, 100, 50, 30, 20, 10, 7, 5, 4 hPa) by the average ozone partial pressure from 1994 to 2008 corresponding to that pressure level. The variation in total ozone was reached up to around 4% in the largest case. The standard deviation in the relative differences of total ozone integrated values by lot was around 1%, and that between production lots was around 0.6%. As per Section 5.3, we showed that the pump correction factors tended to increase, but when a decreasing tendency...
was seen with converted conversion to total ozone integrated values, it tended to decrease. The fact that there is a step observed after 2014 is consistent with the drop-off of total ozone discussed pointed out by Stauffer et al. (2020a, 2020b).
コメントの追加 [諸藤70]: Replaced according to Referee#3’s comment
“Lines 403-406 (and Figure 17 caption): I am confused by this description. Should you not simply calculate the difference, for each sounding, in the total ozone found using your measured pump corrections to that using the average pump correction curve (either CMDL or your average before serial #24000 – or after serial #24000)?”
Figure 17: Top: Estimated impacts on total ozone integrated values with use of the average pump efficiency correction table. Bottom: Impacts on total ozone integrated values for each serial number lot, with error bars indicating standard deviation. (Upper) Estimation of impact on total ozone integrated values when using average pump efficiency correction table. (Lower) The impact on total ozone integrated values for each serial number lot, with the error bars indicating the standard deviation.

6 Conclusion

The unique JMA has succeeded in developing a unique system for measuring pump efficiency, and reported here has enabled fully automatic measurement of individual ECC ozonesondes' pump efficiency. Based on the time-series representations of the individual pump correction factors, these factors, which have been calculated by JMA using this system, indicate temporal changes and also that they vary depending on the production lot. These effects can be attributed to differences in the characteristics of mechanical pumps and motor characteristics of the system. In this situation, if a table of correction values for the pump flow rate correction factor is used without individual pump efficiency measurement, the total ozone value will be affected by up to around ±4%. 

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Systematic biases introduced in ozonesonde observations due to a change in the pump performance variations can lead to erroneous stratospheric vertical ozone trend values. In order to avoid the influence of the lot-dependent pump correction factors in relation to EN-SCI's ozonesondes on the stratospheric ozone trends and to enable accurate determination of detect the actual atmospheric changes with high accuracy, it is advisable we recommend to determine investigate the pump efficiency of each lot to pinpoint understand the trend of the pump correction factor trends and to enable adaptation it to the calculation of ozone concentration. Although the production costs of this system production was not so reasonable to introduce easily may at this moment hinder introduction at present, we hope any commercialization may enable the use of similar systems be commercialized at lower cost in the near future at a reasonable cost.

Code and Data availability

Code and data from this study are available from the authors upon request.

Competing interests

The contact authors have declared that neither they nor their co-authors have any competing interests.

Author contribution

TN led conceptualization and development of the automated pump efficiency measuring system. ATM and TN led the analysis was performed presented here and prepared the paper and reported by TM and TN.

References


World Ozone and Ultraviolet Radiation Data Centre: Dataset Information: OzoneSonde, http://dx.doi.org/10.14287/10000008.