B-4.4 Development of Airborne Instrument for the Greenhouse Gas Flux Measurements(1)

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ABSTRACT This research aims the establishment of flux measurement technique of global warming gases, such as, carbon dioxide, by way of an aircraft. For this purpose, atmospheric air is sampled and temperature, humidity and air velocity data are measured in conjunction with flight maneuver data. Correlating measured gas concentration and vertical air velocity, the flux of the gas can be obtained. In 1996, the ultrasonic anemometer was calibrated in the wind tunnel and in-flight experiments of the probe mounted on the aircraft were performed.

Key Words : Global Warming Effect Gases, Flux measurement, Environmental Flight Testing, Ultrasonic Anemometer, Greenhouse gases

1. Introduction

There are many data presented on the concentration of global warming gases. Only the gas concentration data cannot tell the mass transportation, source or sink. To investigate the source and sink of those gases in the field, we have to know the flux, that is, mass transportation indicating the direction of the gas movement. The precise and prompt measurement of the gas concentration and the three dimensional velocity components at once make it possible to get the flux.

Generally, an aircraft is very useful to investigate the vast area in less time at required condition of the day, weather and season. Present report aims to establish the measurement technique of the flux in flight.

2. Test plane and the apparatus on board

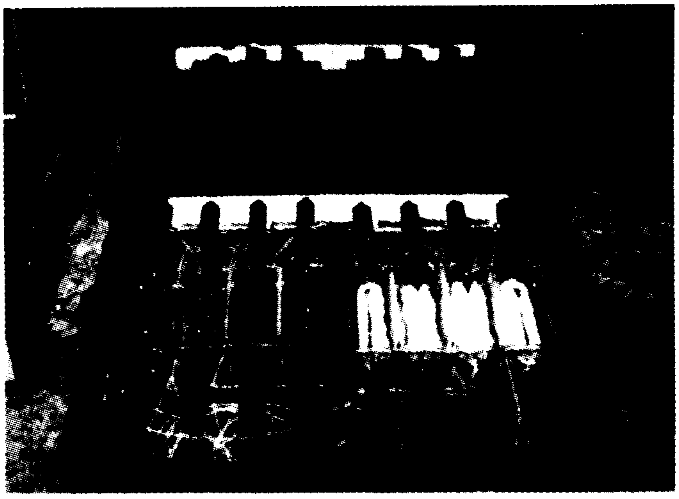

Figure 1 Glass flasks in a suitcase

Two gas sampling ports were provided on the top of the Beechcraft B-65, which belongs to the National Aerospace Laboratory. The ports are made with stainless steel but one of the tube interior was coated by Teflon so as to avoid the wall reaction of the highly reactive gases, such as Ozone. The other one is used for analyzing the gases such as carbon monoxide and dioxide. For separate laboratory analysis, a set of glass bottles which are contained in a travel luggage (Figure 1) is prepared and the air can be sampled at program controlled sequential time by micro-computer during the flight. Periodic air samples are obtained in the atmosphere over the Sagami bay. Ordinarily, the air is sampled several altitude levels between 500 and 7,000 meters in height.

3. Wind velocity measurement by ultrasonic anemometer on board

Figure 2 shows air speed in z-direction, i.e., "Vz" on the aircraft coordinate measured by the ultrasonic anemometer. The figure also shows the rate of climb "R/C" and pitch angle, "θ", measured by Inertia Navigation System(INS). The vertical wind velocity on the airplane was given by the following equation:

$$Wwind = Vz\cos\theta - Vx\sin\theta + R/C + Lq \qquad (1)$$

where, L and q are the distance from weight center to the Pitot tube and pitch rate, respectively. At higher altitude than 5500 m, the output of the ultrasonic anemometer became unstable. The reason of this phenomena was supposed as that the true air speed increases due to the decrease of the density as the altitude increases, although the flight is usually made by the indicated air speed measured by kinetic pressure being kept constant. Later analysis shows that the acoustic impedance decrease due to the decrease of air density and it causes the poor sensitivity of the sensor.

The cause of the sudden change of the vertical wind speed at 1,500 and 2,500 seconds comes from the reason being out of the measurement limit, which is 5,000 m in maximum, of the barometer which supplies the data to the INS. On account of this reason, the average output remained zero though the aircraft goes up and down between 1,500 and 2,500 seconds. The fluctuation of the vertical wind speed after 3,300 seconds caused from the malfunction of the connector. Therefore, correct data were obtained for the time period from zero to 1,500 seconds and from 2,500 to 3,300 seconds.

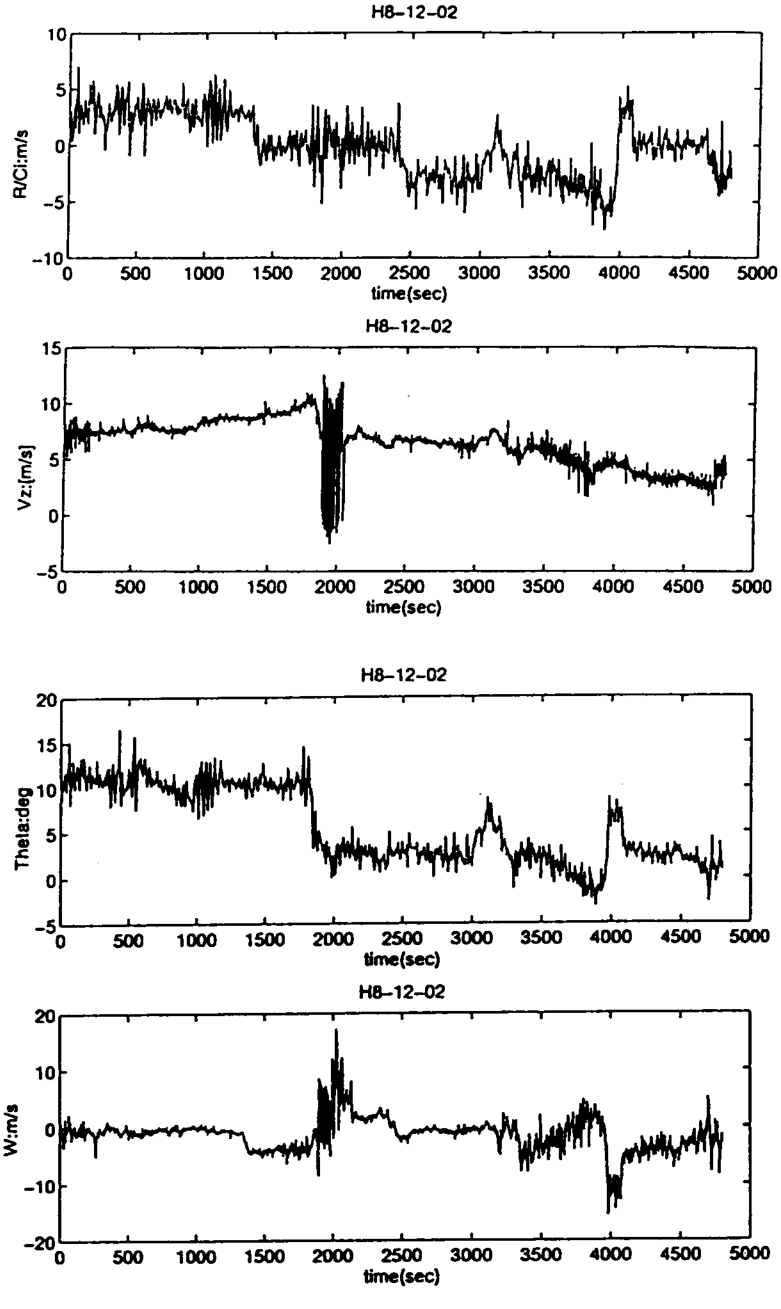

Figure 2 Vertical wind speed measured by ultrasonic anemometer and INS

4. Wind tunnel test of ultrasonic anemometer

The first transonic wind tunnel test:

At the previous flight tests, the deterioration of the ultrasonic anemometer output was found at high altitude. The wind tunnel test was made to find the cause of the deterioration of the anemometer performance at the same pressure conditions equivalent to 4,600 m in altitude. It was found that the pressure reduction makes the poor output on the ultrasonic sensor.

Other than this problem, the noise due to high velocity stream was investigated by changing the configuration of the anemometer probes. It was confirmed that the performance could be improved by smoothing the flow around the sensors. The improvements on the anemometer for above findings expanded the upper limit of the measurement range from 60 to 70 m/s.

From the experimental data obtained by the wind tunnel tests, the sensor output was calibrated was made as following processes;

The sensor model matrix T was defined as,

$$\mathrm{Vxyz} = \mathrm{T\,Vabc} \qquad (2)$$

where T is a model matrix 3*3. The Vxyz is a three dimensional output vector. The Vabc is a three dimensional sensor output vector. The model parameter matrix T was determined as the value to minimize the error between the three dimensional output vector and the wind tunnel test data. As the result of this manipulation, the accuracy within ± 0.7% of the value was obtained. The T matrix consists of:

$$\mathrm{T} = \begin{bmatrix} 1.886 & 1.898 & 1.936 \\ -0.0096 & 0.5398 & -0.5413 \\ -0.628 & 0.302 & 0.3152 \end{bmatrix}$$

The second transonic wind tunnel test:

The second series of transonic wind tunnel tests were performed to investigate the performance at higher velocity range for two types of the anemometer probes. The first sensor probe tested had a stream-lined cover on the sensing rod to minimize the unsteady behavior at the high wind velocity (Figure 3). The second sensor probe has three pairs of sensors on two couples of mount-shafts angled each other by 10° (Figure 4). On the couple of horizontal mount-shaft, two pairs of sensors are fixed inclining ±20° forward with respect to the Y-axis. This configuration makes it possible to measure the horizontal

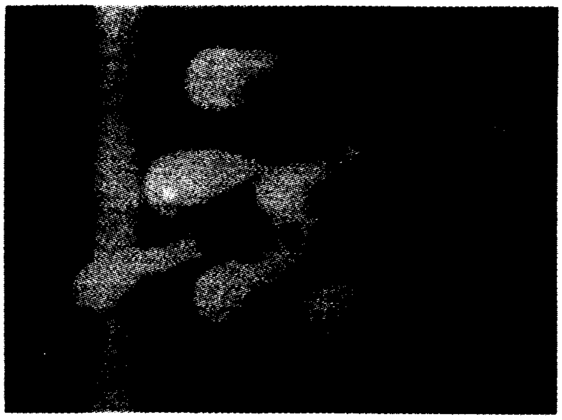

Figure 3 The first sensor probe with stream-lined cover

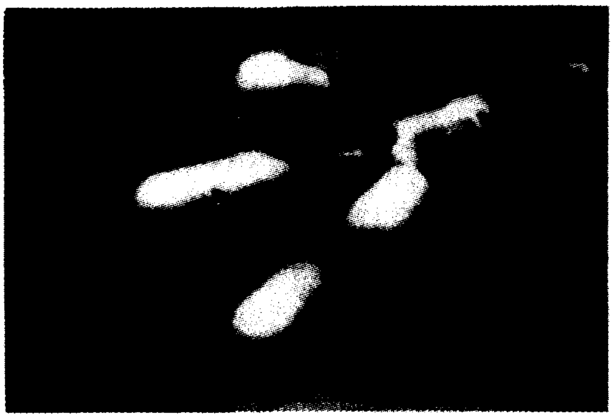

Figure 4 The second sensor probe having three pairs of sensors on two couples of mount-shafts

velocity components. Another pair of sensors is set vertical for measurement the vertical velocity component. The first sensor probe covered was tested to know the pressure effect at atmospheric and low pressure conditions, e.g., 570mbar, which corresponds to the pressure at 4,600 m in altitude. As the result of this, it was confirmed that the sensitivity is proportionally decreased with respect to the decrease of ambient pressure.

At the wind velocity level of 90 m/s, the sensor output became unstable due to the acoustic noise. But it was relatively small compared to the level of the uncovered probe. This fact indicates that the proper aerodynamic consideration of the design on the probe shape will decrease the acoustic noise furthermore. The vertical component sensor installed parallel to the mount-shaft enable to measure higher velocity air stream.

The matrix of the first sensor covered is expressed as :

$$T = \begin{bmatrix} 1.7317 & 1.7129 & 1.7599 \\ -0.04815 & 0.6681 & -0.6627 \\ -0.8221 & 0.3881 & 0.4108 \end{bmatrix}$$

The matrix of the second sensor covered is :

$$T = \begin{bmatrix} 1.3591 & 1.3342 & -0.02025 \\ 0.7159 & -0.7015 & -0.01543 \\ 0.01224 & -0.002781 & 1.2603 \end{bmatrix}$$

Applying transonic wind tunnel test data to the data obtained in the flight tests, the temperature output resulted in nearly constant value independent on the air speed with the following compensation on the vertical component which is perpendicular to the sensor shaft.

$$Tc=Tm+(To)(Vn^2/Co^2) \qquad (3)$$

where, Tc indicates the temperature after the compensation, while Tm is the temperature before the compensation. To and Co are the standard temperature, i.e., 273.15K, and sonic velocity at the temperature, i.e., 331.45 m/s, respectively.
Vn indicates the vertical velocity component with respect to the sensor axis.

It was confirmed that the second sensor has stable operation range up to the velocity level of 80 m/s. The sensors parallel to the mount-shaft had the least noise level.

5. Flux measurement on board

The flight tests were carried out over the Kushiro bog in Hokkaido in July 1996 as the measurement demonstration. From some reasons, the tests were made by the Dornier 228 plane which provides a pentagonal (five-hole) Pitot tube anemometer. The anemometer also can give three-dimensional velocity components as the ultrasonic anemometer investigated.

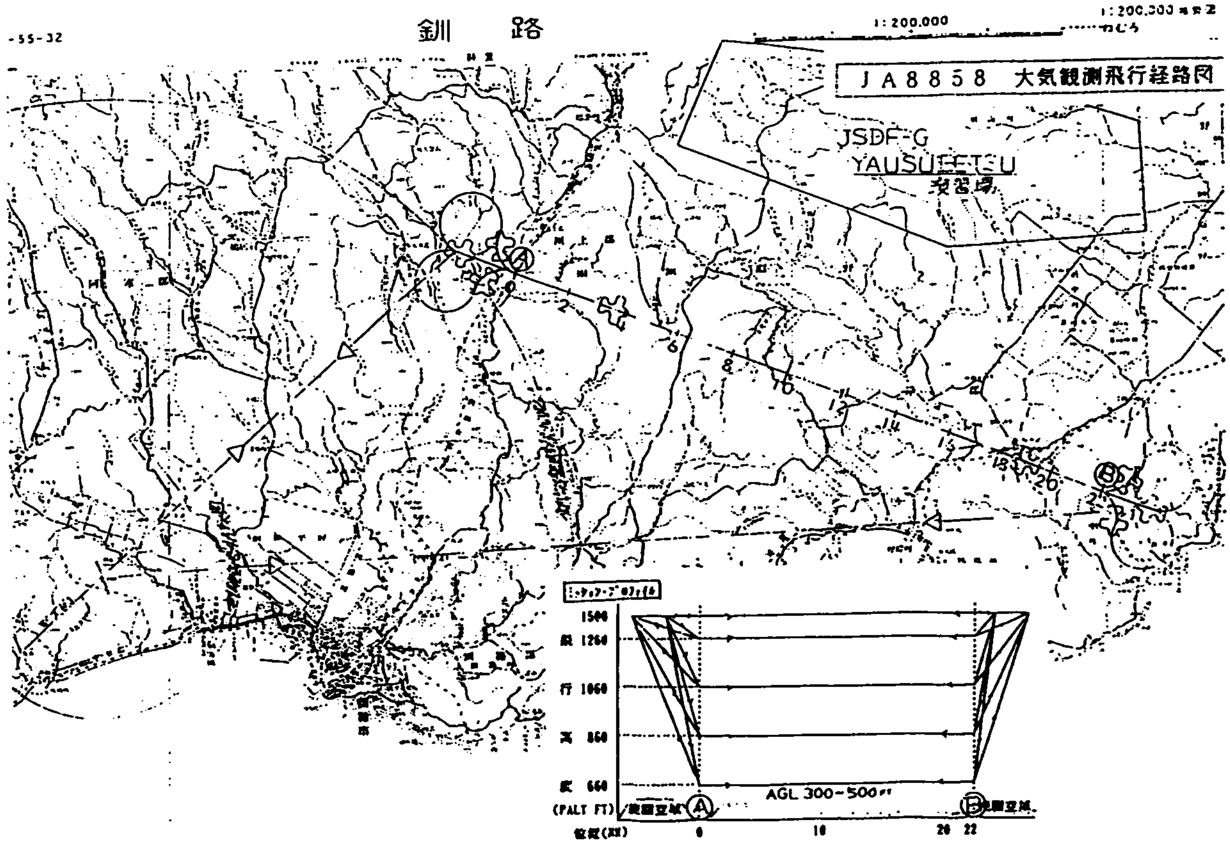

Figure 5 The course of flight tests over the Kushiro bog in Hokkaido.

1) Flight course and data obtained

Taking-off the run-way of the Aerospace Park, Taiki-cho, the airplane directed to a start point A, which is located northwest of Kushiro bog as shown in Fig. 5, the measurement was made from A-point to B-point which is east-south-east direction from A-point. The distance between those points is 40 km. The airplane flew to and from the points at the speeds 55 m/s approximately, varying the altitudes 200, 260 and 320 meters, respectively. Measured data include concentration of the carbon dioxides, humidity, temperature, location, velocity, altitude, attitude angle and others.

2) Measurement of wind speed

The pentagonal Pitot tube on the Dornier plane has a front hole to measure the total pressure and each of four holes is on respective face of a quadrangular pyramid mounted on the stay. The attack angle is measured by the pressure differences between top and bottom faces. The side-slip angle is measured from the pressure differences between right and left faces. Kinetic pressure is calculated from the total pressure measured at the front hole and the static pressure obtained from the other four holes. The velocity can be calculated from the total pressure and the static pressure data.

From the velocity and the attack angle given by the five-hole Pitot tube measurement, the vertical velocity with respect to the aircraft frame axis can be calculated. To calculate the vertical wind speed perpendicular to the inertia axis, it is necessary to change the coordinate to compensate the inclination by the pitch angle. Further more, since this wind velocity includes the vertical inertia velocity of the aircraft, the compensation is needed on it. The following equation is used for the compensation.

$$\mathrm{Wwind} = U \sin(\alpha - \theta) + R/C + L\,q \qquad (4)$$

where U, α and θ are air speed, angle of attack and pitch angle, respectively. R/C, L and q are rate of climb, the distance from weight center to the Pitot tube and pitch rate, respectively. The pitch angle θ, pitch rate q and rate of climb, which are necessary to compensate the motion of the aircraft frame, were obtained by INS. Since the angle of attack α often gives larger value than the real one due to the interference of the fuselage and the main wings, a compensation is needed for the scaling factor which is 0.84 in the case of Do-228.

3) Flux calculation

Other than the carbon dioxide, the humidity was also measured on board by a hygrometer. Then the fluxes of the carbon dioxide as well as humidity were calculated.

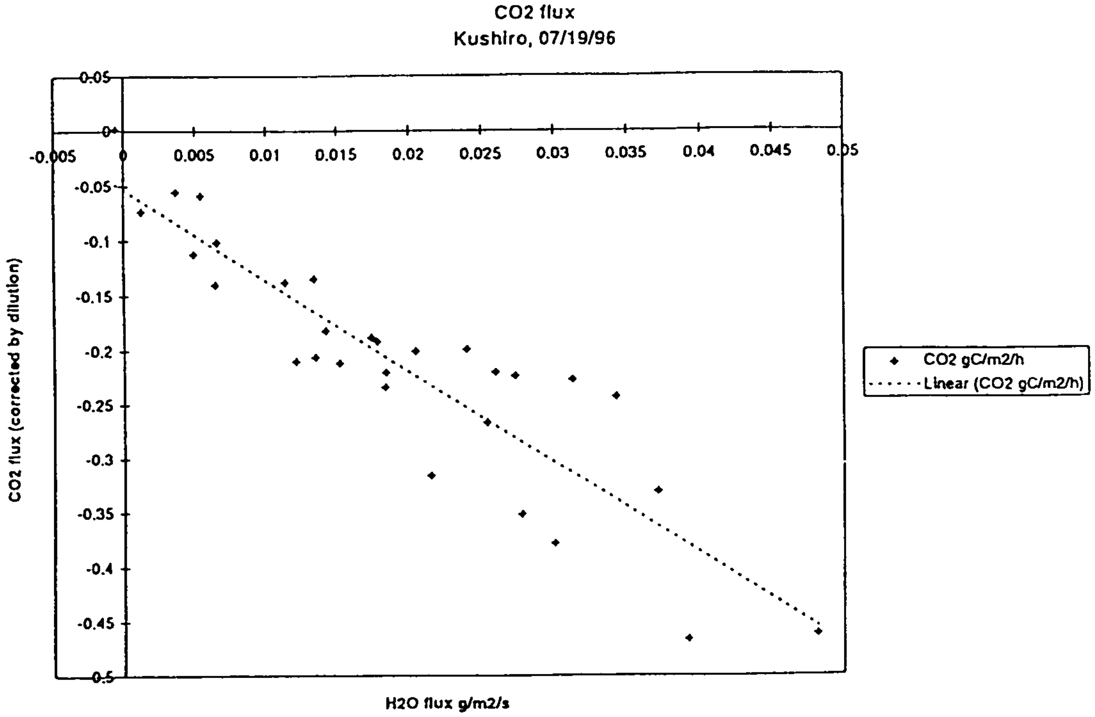

Figure 6 The carbon dioxide flux having high correlation with the water vapor flux

To calculate the flux of a gas, correlation between the gas concentration and the vertical wind velocity must be given.

$$F_T = \langle c' \cdot w' \rangle = \langle c \cdot w \rangle - \langle c \rangle \cdot \langle w \rangle \qquad (5)$$

where c' is the fluctuation of gas concentration derived from the time averaged value. Letters c and w indicate the gas concentration and wind velocity, respectively. The flux defined by eq.(5) depends itself on the definition of the averaging procedure, denoted by brackets. There occurred some phase differences between the fluctuations of the sampled gases and the velocity, since there were some time delays in gas transportation through the tube and by the procedures of the gas analysis. For the compensation of the phase difference, the time delay caused by the gas transport and the analysis was determined by correlating the fluctuation of both of the time dependent data. It gave 4 seconds in the time delay in the carbon dioxide gas and 0.5 second for the humidity.

Compensating these phase differences between air data and gas concentration, flux values were obtained as shown in Fig. 6. The figure shows that the carbon dioxide flux have negative values, i.e., "sink" in the measured area and that the water vapor fluxes have positive value(3, i.e., "generation" .

Above results proved that the flux of gas in the atmosphere can be measured distinctly by the aircraft.

6. Conclusion

1) NAL experimental airplanes were installed and systematized with anemometer and gas analyzer for the environmental observation on global warming gases. It made possible in-situ measurement on carbon dioxide and water, and off-line analysis by bottle sampling.

2) The ultrasonic anemometer for three-dimensional air velocity components was developed. Wind tunnel tests proved that the maximum velocity measured by the anemometer is 80m/s with the accuracy of 0.7%. By compensating the velocity data, it could give the temperature data as well.

3) It was found that the ceiling of the maximum velocity that can be measured by the ultrasonic anemometer decreased at high altitude. It is supposed that the energy transfer to the sensor becomes less in small air density at high altitude and it deteriorates the sensitivity of the anemometer sensor. Moreover, the flight usually keeps instrumental velocity, which is based on kinetic pressure, constant but it actually makes true velocity increase in high altitude due to decrease of air density. The true air velocity, which affects to the acoustic noise, reaches to its upper ceiling velocity at low instrumental velocity in high altitude condition. Therefore, for the use of the anemometer at high altitude condition, it will be necessary to increase the ceiling velocity by improving the stream around the sensor
and by minimizing the acoustic noise.

4) The demonstrative measurement flight tests were carried out over the Kushiro bog in Hokkaido. The vertical velocity were derived from the air speed, the angle of attack by a five-hole Pitot tube, the pitch angle and the rate of climb measured by and INS. From correlation of the fluctuation of vertical velocity and in-situ analyzed gas data, the time delay of the gas with respect to the velocity data was calculated. Then the local fluxes of the carbon dioxide and water vapor were obtained over the bog. It was confirmed that the measured carbon dioxide flux has high correlation with the water vapor flux.

5) Present tests and the flux measurement technique demonstrated by airplane was the first trial in this country at least and it would give prospective tool to investigate the global atmospheric environment.

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