A Study on Measurements of Head Loss in Tunnels (On Control of Temperature in Measuring Device)

MEMOIRS OF THE FACULTY OF ENGINEERING
FUKUI UNIVERSITY
VOL. 34 No. 1 1986

A STUDY ON MEASUREMENTS OF HEAD LOSS IN TUNNELS
(On Control of Temperature in Measuring Device)

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(Received Mar.1, 1986)

The purpose of the research is to develop the measuring device of the head loss in tunnels. This device measures the differences of pressures between two points, using two independent devices of the same construction, in order to obtain the head loss of tunnels. This device is composed of a container in which the air pressure is kept constant as the reference pressure, and is equipped with a manometer to detect the difference between the reference pressure and the ambient air pressure.

In order to obtain the exact constant pressure, it is necessary for the container of the device to be kept at a constant temperature with the accuracy of 10^{-3}°C. Firstly, both the structure and its operation of the device with double-walled container is explained. Secondly, the dynamics of temperature may be represented as an on-off control system and its characteristics of temperature is analyzed in detail. Finally, the experimental studies are performed and the good regulation may be obtained at the high accuracy within 10^{-3}°C.

I. INTRODUCTION

For the design of the ventilator used for fresh air transit in the road tunnels or galleries, it is necessary to observe the

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flow rate of air and to measure the head loss of tunnels. The head loss of tunnels can be calculated by measuring the difference of pressures between both sides of tunnels and the air flow in tunnels. The flow rate of air is obtained through multiplying the average air velocity by the sectional area in tunnels, where the air velocity is measured by a hotwire anemometer or an anemometer. Then, it has been expected to develop a device which measures the differences of pressures between two points.

Up to now, there are few methods concerning with the measurement of difference of pressures between two points. The classical method is to use a pitot tube and a rubber tube, in which the pitot tubes at each of two points are connected by a rubber tube and the difference of pressure is measured. However, in the case of a road tunnel which might be several kirometers in length away, the length of the rubber tube becomes too long and then the inaccuracies are too great. Another method is to use a barometer at each of the two measuring points, in order to obtain the required value from the difference of absolute pressures. Unfortunately, This method can not be adopted, because, even by the use of very precise barometers, in the road tunnels, the differences of pressures measured are often too small comparing with the absolute pressure of the each points and also the flow rates of air are not steady enough, due to atmospheric fluctuations.

Lastly, a third method enables satisfactory results to be obtained. This method is to use a precision manometer which, at each points of measurements, compares the atmospheric pressure with the absolute pressure which is called the reference pressure. The difference in the values measured at each or the two points gives the required value of the difference of absolute pressures. The reference pressure is obtained as the air pressure which is kept constant, maintained at constant temperature in the container of the constant volume. In the first stage, in order to hold at constant temperature, melting ice was used by one of authors.[1] But, it is too difficult to obtain the desired precision except in a laboratory because it is necessary to bring to the various places and to keep the ice long enough. After that, J.Oliver et al[2] developed the devices with electric regulation of temperature, in which the accuracy of regulation is imposed by the deviation of temperature of 10^{-3}°C, which is called Statstat. This device might operate with a sufficient accuracy. However, its consumption of electric power is approximately 500W, and its mass approximately 300kg. Then, this device may be too large-scaled to the practical use.

The object of this study is to develop the measuring device which measures the difference of pressures, by means of the detection of the difference between the reference pressure and the ambient air pressure.[3] This device is newly devised to keeping a sufficient accuracy and handy to carry. The most important part of this device is a container which produces the reference pressure.

Now, letting the pressure inside the container p Pa, the absolute temperature T°K, the spacific volume of air v m^3/kg and the gas constant R J/(kg·K), the following relation holds,

$$pv = RT.$$

Supposed that v is a constant, it follows that

$$dp = R\,dT/\,v = R\rho\,dT\ .$$

Since the density of air ρ is about 1.2 kg/m^3 and R is 287 J/(kg·K), we have

$$dp = 340\,dT\ .$$

If we demand the accuracy within 0.4 Pa on the measuring device, it is necessary for the container to be kept at a constant temperature with the accuracy of 10^{-3}°C. This paper presents both theoretical and experimental results concerning with the temperature control of the container in the measuring device.

2. Structure of Thermostated Device

The structure of thermostated device is shown in Fig.1, which consists of double-walled containers. The outer casing is made of the styrene form and the inner one the special glass covered by the styrene form. The space between two casings is called as the intermediate space. The intermediate space can be thermostated at 50°C by the on-off regulation of the heater. The regulator can be precisely controlled using a platinum temperature sensor. From this regulation and heat transfer characteristics of the inner vessel, the inner space can be structurally kept at a constant temperature with higher accuracy, comparing with the one of intermediate space. In the intermediate space, the small fan to uniform the temperature in the space, thermometer and the pressure tranceducer to detect the difference of the pressure between the atmosphere and the inner space are settled. As this device must be portable, the

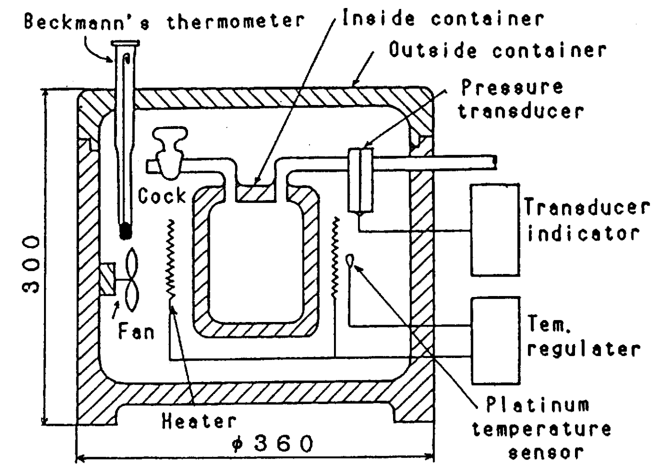


Fig.1 Structure of temperature-controlled device

precise temperature regulator with DC 12 volt is used and the electric control circuit is shown in Fig.2. For the detection of temperature, four pieces of platinum temperature sensors connected with series are used. The output of sensors is amplified of 10,000 magnifications and afterwards, through the schmidt trigger circuit, the on-off control of the heater is carried out. The greatest care in this circuit may be taken in the stability of the standard voltage circuit and, furthermore, this circuit may be also held at a constant temperature in the intermediate space. The total weight of the temperature-controlled device is about 10kg including the electric source (i.e., a storage battery).

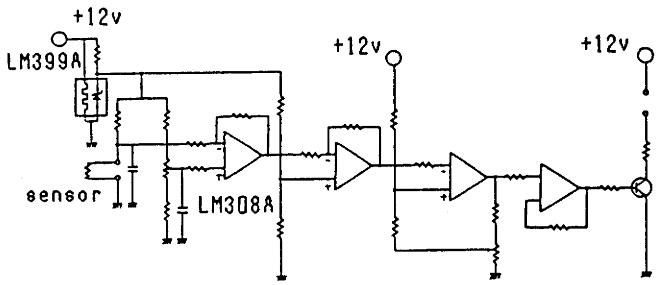


Fig.2 Electric control circuit

3. Analysis

3.1 Derivation of Basic Equation

The physical model of temperature-controlled device in Fig.1 is shown in Fig.3, which is the system with double-walled structures composed of inner and outer containers.

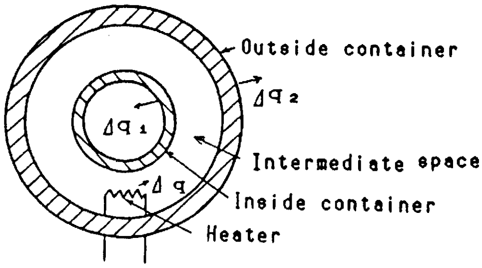


Fig.3 Pysical model of temperature-controlled device

The principal symbols are denoted as follows:

- c_0, c_1 ; heat capacities of intermediate and inner spaces
- σ_0, σ_1 ; heat transfer coefficients of inside and outside container
- G_0, G_1 ; transfer functions of intermediate and inner spaces
- $\Delta\theta_0, \Delta\theta_1$; temperature of intermediate and inner spaces
- Δq ; total heating value generated from electric heater and fan etc.
- $\Delta q_1, \Delta q_2$; quantities of heat transferred to inner space and atmosphere from intermediate space, respectively

where Δ presents the difference between the reference state in the intermediate space and the real data.

Supposed that the quantity of heat is proportional to the difference of temperature between inner and outer spaces, the following relations holds,

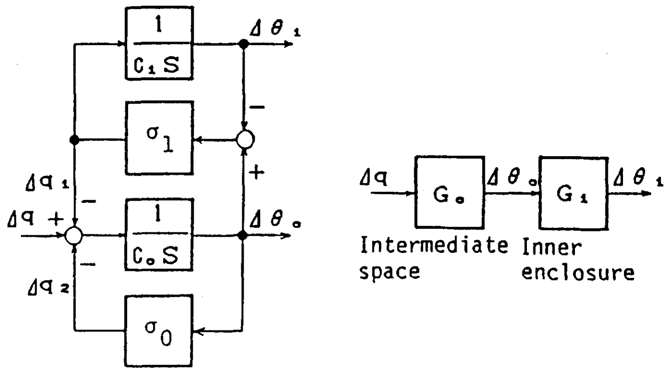
$$\Delta q_2 = \sigma_0 \Delta\theta_0 \tag{1}$$

$$\Delta q_1 = \sigma_1(\Delta\theta_0 - \Delta\theta_1) \tag{2}$$

Since the quantity of heat transferred to each containers causes the raise of temperature, we obtain,

$$\Delta q_1 = c_1 \frac{d\Delta\theta_1}{dt} \tag{3}$$

$$\Delta q - (\Delta q_1 + \Delta q_2) = c_0 \frac{d\Delta\theta_0}{dt} \tag{4}$$



(a) (b)

Fig.4 Block diagram of heat transference

Using the relations (1) to (4), the block diagram of the heat transference is shown in Fig.4(a). If we define the transfer function G_0 of intermediate space as $\Delta\theta_0/\Delta\theta$, it follows that

$$G_0 \triangleq \Delta\theta_0/\Delta\theta = \frac{c_1 s+\sigma_1}{c_0 c_1 s^2+(c_0\sigma_1+c_1\sigma_1+c_1\sigma_0)s+\sigma_0\sigma_1} \tag{5}$$

Also, defining the transfer function G_1 of the inner space as $\Delta\theta_1/\Delta\theta_0$, we obtain

$$G_1 \triangleq \Delta\theta_1/\Delta\theta_0 = \frac{1}{(1+T_1 s)} \tag{6}$$

where $T_1=c_1/\sigma_1$.

Using Eqs.(5) and (6), the block diagram of Fig.4(a) is simplified as shown in Fig.4(b).

3.2 Transient Response

When the electric power is supplied to the heater, the temperature in the intermediate space is rising and reaches to the reference temperature. At this time, as the overshoot and amplitude are too small, it can be assumed that the temperature in the intermediate space is kept constant immediately at the point in time when the temperature becomes the reference one, which is higher $\Delta\theta_c$ than the atmospheric temperature. Let t_0 be the time when the temperature in the intermediate space gets up at $\Delta\theta_c$ for the atmospheric one and $\Delta\theta_{1c}$ be the temperature in the inner space at time when the temperature in the intermediate space arrives at $\Delta\theta_c$. Then, the transient response with respect to the temperature in the inner space can be obtained for the time interval $0 \le t \le t_0$ as the step response when the input Δq is added to the intermediate space, where initial conditions are $\Delta\theta_1=0$ and $\Delta\theta_0=0$. Using Eqs.(5) and (6), the following result is obtained.

$$\begin{aligned}\Delta\theta_1 &= L^{-1}\{G_0(s)G_1(s)\frac{\Delta q}{s}\} \\ &= \frac{\Delta q\sigma_1}{c_0 c_1}\{\frac{1}{\alpha\beta} + \frac{1}{\alpha(\alpha-\beta)}\exp(\alpha t) + \frac{1}{\beta(\beta-\alpha)}\exp(\beta t)\}\end{aligned} \tag{7}$$

where

$$\alpha,\beta = -\frac{1}{2}(\frac{\sigma_1}{c_1}+\frac{\sigma_1}{c_0}+\frac{\sigma_0}{c_0}) \pm \frac{1}{2}\sqrt{(\frac{\sigma_1}{c_1}+\frac{\sigma_1}{c_0}+\frac{\sigma_0}{c_0})^2-4\frac{\sigma_0\sigma_1}{c_0 c_1}}$$

Furthermore, in the case where $t \ge t_0$, the response of temperature in the inner space can be obtained by solving Eqs.(2) and (3). Under the condition $\Delta\theta_1=\Delta\theta_{1c}$ at $t=t_0$, it follows that

$$\Delta\theta_1 = \Delta\theta_c+(\Delta\theta_{1c}-\Delta\theta_c)\exp\{(t_0-t)\sigma_1/c_1\} \tag{8}$$

3.3 Stationary Response

The block diagram of temperature-controlled system is shown in Fig.5. In this figure, K is a magnification of the amplifier. Also, let K_s be a temperature coefficient of the sensor and T_s be a time constant of the sensor. Then, the transfer function G_s of the sensor is given by

$$G(s) = K_s/(1+T_s s) \tag{9}$$

For the relay element in Fig.5, let 2h be a hysterisis width, z an

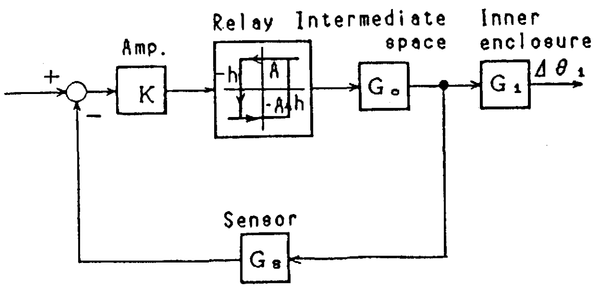


Fig.5 Block diagram of temperature-controlled system

input amplitude and 2A an output magnitude. Then, the relay element can be represented by the following describing function G_d,

$$G_d = 4A/(\pi z) \angle -\sin^{-1}(h/z) \tag{10}$$

Using Eqs.(9) and (10), the characteristic equation of the temperature-controlled system is obtained by

$$1 + KG_dG_0G_s = 0 \tag{11}$$

Rewritting Eq.(11), we have

$$KG_0G_s = -1/G_d \tag{12}$$

The left-hand and right-hand sides of Eq.(12) are the functions of input frequency ω and input amplitude z, respectively. Then, as shown in Fig.6, we can find out ω and z of self-oscillations of this system from the intersection of vector locus for both sides of Eq.(12).

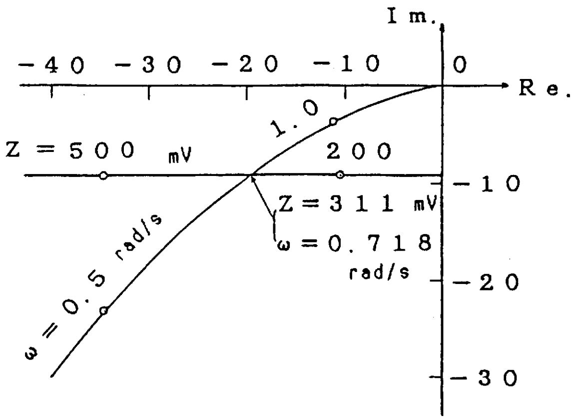


Fig.6 Vector locus for Eq.(12)

4. Experiments

4.1 Parameters of Device

In order to examine the characteristics of the experimental apparatus, each parameter values of the device are set as follows. The heating values of the device and fan are q_h=222W and q_f=6.0W, respectively. The parameters of the device were set as K=10,000, h=131mV, K_s=4.95mV/°C and T_s=3s. Furthermore, from the transient response examination for the inner and outer containers, parameters with respect to each containers were determined as c_1=320J/°C,

σ_1=0.310W/°C, c_0=1,190J/°C and σ_0=0.406W/°C.

4.2 Transient characteristics

The experimental results of transient response for the temperature-controlled device are shown in Fig.7. The real line is the theoretical result calculated by Eqs.(5),(7) and (9) and the symbols o and Δ the observed data. Both the theoretical and experimental results show the good agreement. Here, the temperatures in both inner and intermediate spaces were detected using precise thermister thermometer. The settling time for the inner space to be within the allowable temperature 0.001°C, is about 3.3 hours by the calculation of Eq.(8).

4.3 Stationary Characteristics

The characteristics of the temperature in the device is examined in the stationary states. From the vector locus shown in Fig.6, it can be seen that the period of self oscillation generated in this system is 8.8s and the input amplitude z to the relay element is 3.11mV. From this result, it follows that the temperature deviation in the intermediate space is about 0.015°C. Also, using Eq.(6), it can be calculated that the temperature deviation in the inner space is about 2.0×10^{-5}°C.

Figure 8 is an example of experimental results in the case where the atmospheric temperature is 7.9°C, which shows a sample run of

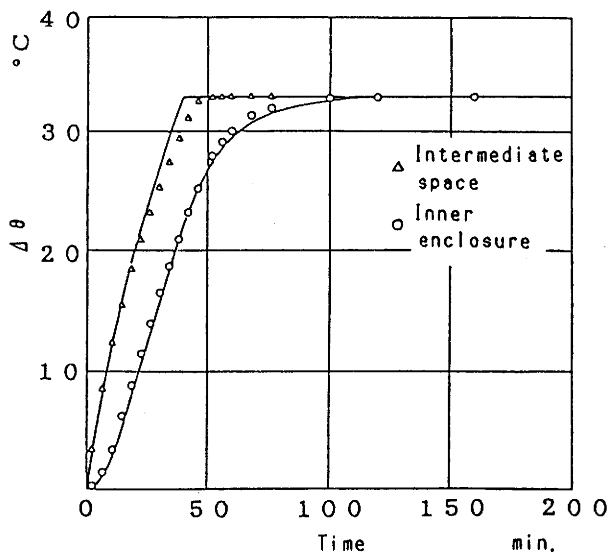


Fig.7 Transient response of temperature-controlled device

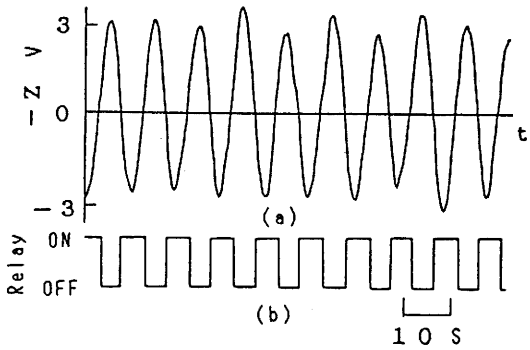


Fig.8 An example of self oscillation in the case where the atmospheric temperature is 7.9°C

self oscillations in the intermediate space. Figure 8(a) shows the input amplitude z to the relay element and (b) the output signal of the relay element. From this result, the switching period of relay is about 9 or 10 sec and the input amplitude z is about 3V. The experimental result of the period agrees with the theoretical one, but the input amplitude z is about 10 times, comparing with the theoretical value. It may be considered for the reason that the temperature in the intermediate space is not uniform because the stirring of the air flow in the space is not sufficient. From the above experimental result, it can be estimated that the temperature variation in the inner space is about 2.0×10^{-4}°C by the theoretical calculation. However, at present, we can not obtain the positive proof for this accuracy, because the measurement of the microscopic temperature is very difficult.

5. Influence of Atmospheric Temperature

In this section, we shall consider how the change of atmospheric temperature influences for the temperature control in the device. Define $\gamma(<1)$ the rate of on-action time of relay output in one period of self oscillation. Since the relay element becomes non-symmetry by the change of atmospheric temperature, the value of γ varies and then the average value of the self oscillation shifts from desired temperature. Here, we shall analyze how the control temperature shifts from the desired one in the case where the relay element is non-symmetry.

Now, let θ_1 be the atmospheric temperature in the case where the relay element is symmetric, that is, $\gamma=0.5$ and θ_a be the practical atmospheric temperature. Also, $\Delta\theta_a=\theta_a-\theta_1$.

5.1 Analytical Method

When there exists the stationary self oscillation in the relay system (angular frequency ω), every variables which characterize the states vary with same angular frequency ω. Now, let $Z(t)$ be the input variable to the relay element which varies periodically, $X(t)$ be the output variable in the linear portion of closed loop system shown in Fig.5 and $Y(t)$ be the output variable from the relay element. The following relation holds between $Z(t)$ and $X(t)$, from the closed loop condition,

$$Z(t) = -X(t). \tag{13}$$

Accordingly, from the existence condition of self oscillation and Eq.(13), it follows that , for the switching time of relay

$$X(2\pi/\omega) = -h, \quad X(\gamma\cdot 2\pi/\omega) = h \tag{14}$$

and, as the switching condition

$$X(2\pi/\omega) > 0, \quad X(\gamma\cdot 2\pi/\omega) < 0 . \tag{15}$$

Here, the transfer function of linear portions of the closed loop relay system in Fig.5 is set as

$$W(s) = KG_0G_s . \tag{16}$$

In the case where the $W(s)$ has a single pole, $X(2\pi/\omega)$ and $X(\gamma\cdot 2\pi/\omega)$ can be written as the sum of Taylor series,[4)]

$$X(2\pi/\omega)=2A\sum_{i=1}^{n} C_i\left[\frac{1-\exp\{s_i(1-\gamma)2\pi/\gamma\}}{1-\exp(s_i 2\pi/\omega)}-\frac{1}{2}\right]+y_0|W_0| \tag{17}$$

$$X(\gamma 2\pi/\omega)=2A\sum_{i=1}^{n} C_i\left[\frac{\exp(s_i\cdot\gamma 2\pi/\omega)-1}{1-\exp(s_i\cdot 2\pi/\omega)}+\frac{1}{2}\right]+y_0|W_0| \tag{18}$$

where y_0 reveals the constant command signal of relay element i.e., $y_0=\Delta\theta_a\sigma_0$. Also, $s_i(i=1,2,\cdots,n)$ is a pole of the transfer function $W(s)$. Letting $W(s)=A(s)/B(s)$, C_i is given by

$$C_i = A(s_i)/(B'(s_i)s_i) . \tag{19}$$

Using Eqs.(17),(18) and (19), we can obtain both ω and γ for each $\Delta\theta_a$, which satisfies the existence conditions of self oscillation, Eqs.(14) and (15).

5.2 Analytical Result

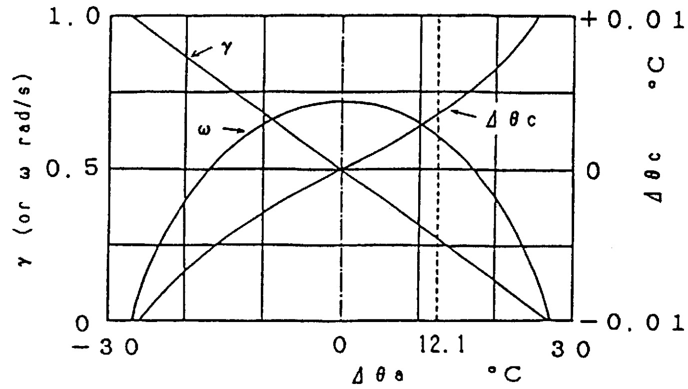


Fig.9 Analytical results (Relations between $\Delta\theta_a$ and ω, γ, θ_c)

Using parameter values of experimental device described in Section 4.1, the calculated results of both ω and γ for each $\Delta\theta_a$ are shown in Fig.9. In this case, the desired temperature is 50°C. In Fig.9, $\Delta\theta_c$ represents the deviation of the average temperature for each γ in the intermediate space, where γ=0.5 is the standard point.

For example, we shall consider the case where the atmospheric temperature is 20°C. Since $\Delta\theta_a$=20°C−7.9°C=12.1°C as shown in dotted line in Fig.9, it can be understood that γ=0.27, ω=0.61 rad/s and $\Delta\theta_c=3.6\times10^{-3}$°C. This fact implies that the average temperature becomes 3.6×10^{-3}°C higher in the intermediate space, comparing with the case where the atmospheric temperature is 7.9°C. Moreover, assumming that the device may be useful in practice for $0.1\le\gamma\le0.9$, the range of atmospheric temperature for this device to be used is from −14.1°C to 29.9°C. Also, from the transfer function Eq.(16) of the inner space, it may be clarified that the amplitude of temperature in the inner space becomes sufficiently small.

5.3 Experimental Consideration

Figure 10 shows the experimental result of the stationary self oscillation in the case where the atmospheric temperature is θ_a= 20°C. From Fig.10, it can be known that the period of switching is about 10 sec and $\gamma\cong0.3$. This result is nearly consistent with the analytical one. The Z(t)-process in Fig.10(a) is obviously non-symmetric. Accordingly, as already described in the analysis, it is clear that the average temperature in the intermediate space

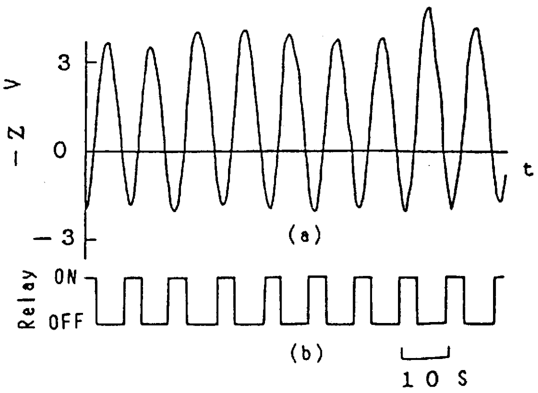


Fig.10 An example of self oscillation in the case where the atmospheric temperature is 20.0°C

shifts comparing with the case of Fig.8, i.e., $\gamma=0.5$. However, it seems that the amplitude of the temperature causes hardly any change. On the other hand, since it is difficult to measure precisely the amplitude of the temperature in the inner space, we could not obtain the experimental result in this case.

6. Measurement of Barometric Difference

Since the barometric difference is obtained by a small difference between two relatively large values, the precision of the manometer must be obviously high. Then, it is unfavorable to connect directly the U-tube manometer, in order to obtain the difference between the reference pressure and ambient one. Because it causes that the air volume in the inner space changes by the movement of water column and then the adiabatic change occurrs. Also, it may be impossible to correct experimental values by performing calculations, since conditions of the correction are too complex. Here, instead of connecting the U-tube manometer to the container directly, it is newly devised to connect indirectly through pressure transducer, supported tank and pump. The outline of the structure for measuring device is shown in Fig.11. In Fig.11, "a" shows the inner container held at a constant temperature and "m" the U-tube manometer and, between them, the supported tank ℓ, pump k and three way cock j are connected. Accordingly, this device does not measure directly the difference between the reference

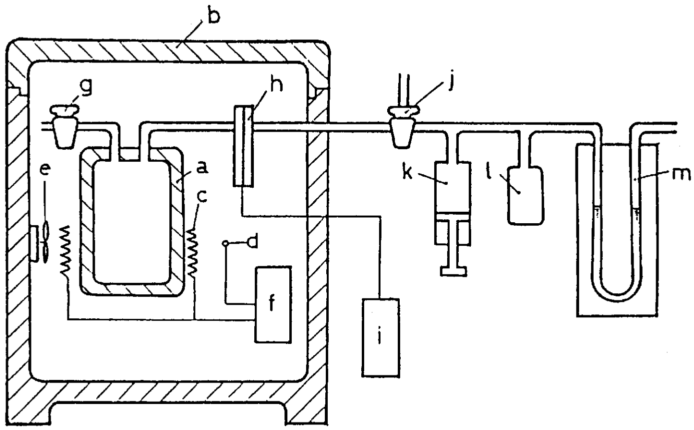


Fig.11 Measuring device of barometric difference

pressure in ℓ and the ambient pressure. The principle of measurement is illustrated as follows. Firstly, it equates the pressure in ℓ to the pressure in "a" and, after that, measures the difference between the pressure in ℓ and the ambient one by the reading of "m". The pressure in ℓ may be changed smoothly by regulating the pump k. The pressure transducer h is used to detect precisely whether pressures in both "a" and ℓ are equal or not. Each symbols of c, e,d, f and i represent heater, fan, thermal sensor, temperature controlled circuit and indicator of the pressure transducer. Also, "g" is a cock by which the air in "a" opens or closes to the atmosphere.

In the practical measurement, after the temperature in "a" is held constant, we close "g", connect both ℓ and h by j, regulate the pump k and, when i indicates zero points, read the value of "m". The reading of "m" suggests the difference between the pressure in "a" and the ambient one.

7. Conclusion

For the measuring device of barometric difference made on trial, the performance of temperature control has been explored thoretically and experimentally, with respect to the temperature controlled container which is one of the most important elements in the device. In consequence, the characteristics for this device can be summarized as follows.

(1) For the deviation of the allowable temperature to be 0.001°C in the inner space, the settling time of this device became about 3.3 hours.
(2) From the experimental results, it follows that the temperature in the intermediate space can be constantly controlled with the deviation of about 0.15°C. Based on this fact, it can be considered that the temperature variation in the inner space is about 2.0×10^{-4}°C.
(3) This device can be used in the range that the ambient temperature is from -14.1°C to 30°C. However, since the variation of temperature becomes about 0.003°C in the inner space for the change of 10°C in the ambient temperature, it is necessary in the interval of measurement that the change of ambient temperature is within 4°C. At present, we are making inquiries to develop more precise device which is possible to be applied for large variation of the ambient temperature.

From above results, it can be considered that the measuring device attains the purpose to use for the measurement of barometric difference between two points.

ACKNOWLEDGMENT

This work is supported in part by the aid for science research of Japanese Department of Education. This support is gratefully acknowledged. The authors also wish to express their appreciation to Messrs. H.UCHIYAMA and H.TSURUBE for their support.

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