Effects of Solar Radiation and Wind Velocity Upon the Temperature Rise of the Pole Transformer

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The temperature rise of the pole transformer, due to solar radiation in summertime, was experimentally measured. On the other hand, a theoretical calculation was carried out to find out what balance the heating caused by the loss of transformer and the solar radiation will maintain in reference to the thermal discharge due to the wind velocity and radiation.

Thus, a study was made to establish whether or not the experimental result might coincide with the theoretical calculation. In other words, an experiment was carried out on the transformer of one kind of capacity only, and, accordingly, effort was further made to find out the possible theoretical result if experiments were made with transformers of different capacities.

1. Introduction

It is assumed that the pole transformer will have its temperature considerably raised when exposed to the solar radiation in summer. A study pertaining to this particular aspect has already been made public by Prof. Mori in J.I.E.E.[1] This study, however, was based on a pseudo-radiation, and, as far as the present writers are informed, no study based on actual solar radiation has hitherto been published.

As a matter of fact, the solar radiatiou is incessantly subjected to changes in its direction and intensity, while the wind velocity, likewise, is always liable to change. For this reason, it is extremely difficult to calculate its effects. The approximate inclination and valve of the effects may well be assumed.

2. Direct Insolation

The solar constant is believed to be roughly $J_0-1.94$ cal/cm^2 m. This energy, while passing through the atmosphere, is dicreased to a certain extent by absorption, and, tnen, reaches tne earth. If its value at this stage is represented by (J), the following equation may be obtained according to Bougner's equation:

$$J=J_0\, p^{1/\sin h} \text{ cal/cm}^2\text{ m} \tag{1}$$

in which, however;

p : transmission coefficient

h : Solar altitude

In the above equation, p grows larger from autumn to winter and eventually becomes

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as large as 0.758[2] at the maximum. Acxually, however, it is extremely seldem that the value exceeds 0.75. Therefore, in this report, the calculation was carried out as $p=0.75$. Now, may be deduced from the equation below:

$$\sin(h)=\sin(\varphi)\sin(\delta)+\cos(\varphi)\cos(\delta)\cos(t) \quad (2)$$

where, however;

δ=Declination (23° 27′ in summer)

φ=Latitude

t=Hour angle

The maximum direct insolation (J) on record was approximately 1.4–1.5 cal/cm² m.[3]

3. Calculation of Direct Insolation

If the value of (J) at each time is deduced from the equation (1), its horizontal and vertical distribution (J_H), (J_V) are deduced from the equation below:

$$J_H=J\sin h \quad (3)$$

$$J_V=J\cos h\,\cos\alpha \quad (4)$$

where, however,

α=Angle formed by the normal on the heat-receiving surface and the horizontal projection of (J).

If, from the equations (3) and (4), the direct insolation received by each surface when one side of a 1 m³ regular solid accurately faces the south, is calculated, the result will be as indicated in Table 1. By

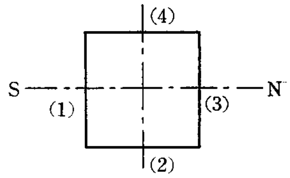


Fig. 1

Table 1 Direct insolation (cal/cm² m)

Time	Vertical wall					Horizontal wall	Total Sum
	(1)	(2)	(3)	(4)	Total		
6	—	0.290	0.122	—	0.412	0.232	0.644
7	—	0.800	0.262	—	1.062	0.548	1.610
8	—	0.937	0.214	—	1.151	0.842	1.993
9	—	0.860	0.156	—	1.016	1.095	2.111
10	0.064	0.642	—	—	0.706	1.290	1.996
11	0.070	0.342	—	—	0.412	1.412	1.824
12	0.024	—	—	—	0.024	1.455	1.479
1	0.070	—	—	0.342	0.412	1.412	1.824
2	0.064	—	—	0.642	0.706	1.290	1.996
3	—	—	0.156	0.860	1.016	1.095	2.111
4	—	—	0.214	0.937	1.151	0.842	1.993
5	—	—	0.262	0.800	1.062	0.548	1.610
6	—	—	0.122	0.290	0.412	0.232	0.644
Sum	0.292	3.871	1.508	3.871	9.542	12.293	21.835

this table, it is known that the amount of heat received on the side surface only is 9.542 $cal/cm^2\,m = 5725\,Kcal/m^2$ day. The maximum occurs at 8 o'clock in the morning and at 4 o'clock in the afternoon, which, respectively, is 1.151 $cal/cm^2\,m = 690.6\,Kcal/m^2\,h$.

The amount of heat received on the upper surface, of course, denotes noon. On the whole, the maximum is seen at 9 o'clock in the morning and 3 o'clock in the afternoon.

In the case of the pole transformer, the oil surface and the cover are considerably apart from each other, and, on that account, the heat received on the upper surface is not assumed to affect the oil temperature to any noticeable degree.

4. Heat Calculating Equations

If the temperature of the coil and that of the core are the same (θ_1), and the temperature of the oil is represented by (θ_2), that of the case by (θ_3), the ambient temperature by (θ_4), the sum of the copper and core loss by (Q_1) and heat received by solor radiation by (Q_2), the following equation may be obtained:

$$Q_1+Q_2=C_1\frac{d\theta_1}{dt}+C_2\frac{d\theta_2}{dt}+C_3\frac{d\theta_3}{dt}+K_{34}(\theta_3-\theta_4) \qquad (5)$$

in which, however:

C_1, C_2, C_3·········Heat capacity of coil and core, oil and case.

K_{34} ··················Heat conductivity between the outer atmosphere and the case.

(1) Formula on heat diffusion due to radiation.

$$a=4.5\left\{\frac{\left(\frac{T_1}{100}\right)^4-\left(\frac{T_2}{100}\right)^4}{T_1-T_2}\right\} \quad (\mathrm{Kcal/m^2\,h}) \qquad (6)$$

However; T_1=Temperature of the case (°K)

T_2=Temperature of the outer atmosphere (°K)

(2) Formula on heat diffusion due to the convection on the vertical wall surface.

Schmidt & Beckmann's formula:[4)]

$$a=4.8\sqrt{\frac{t-t_0}{t_0 H}}\sqrt{\frac{b}{760}} \quad (\mathrm{Kcal/m^2\,h}) \qquad (7)$$

However; b =Reading on the barometer (mm).

t =Temperature on the wall surface (°C).

t_0 =Temperature of the outer atmosphere (°C).

H=Height of the wall surface (m).

(3) Heat diffusion on the horizontal wall surface.

According to Kirpitcheff's experiment, the downwardfacing horizontal wall surface has a value 20% less than that of the vertical wall surface, indicated by equation (7), while the value of the upward-facing horizontal wall surface is larger by 55%.

(4) Formula on heat diffusion on the vertical wall surface by forced ventilation.

Merkel's formula:[5)]

$$a=(\omega P)^{0.87}L^{-0.22}B \quad (\mathrm{Kcal/m^2h\ ^\circ C}) \tag{8}$$

Despite the above, the approximate formula below is also feasible:

$$\left.\begin{array}{ll} a=5.3+3.6\omega & (\omega \leq 5\ \mathrm{m/s}) \\ a=6.47\omega^{0.87} & (\omega > 5\ \mathrm{m/s}) \end{array}\right\} \tag{9}$$

However; ω: Wind velocity (m/s)

5. Experiment

Similarly to the condition of actual use, a transformer was deposited on a pole at height of 4 m above the ground, while another was placed on the ground, and the full load was applied according to the loading back method. The temperature of the coil was measured by calculating the resistance of the coil. And, a thermo-element, consisting of the electrical resistance, manufactured by Yokogawa Electric Co., Ltd. was inserted between the primary and secondary coils, by the use of which measurement was also carried out. In measuring the average temperature of the oil, a fine copper wire was wound around the fiber plate having the same length with the depth of the oil, and it was calculated from the resultant resistance. For reference, a mercury thermometer was used, too. For the measurement of the case temperature, the afore-said Yokogawa's thermometer and a mercury thermometer were used. Other tools used in the experiments were:

Ōyama's radiation meter (Yokogawa).

Robitzsch'e actunometer.

Robenson's anemometer.

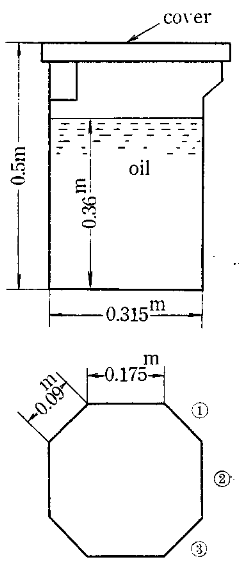
The transformer tested:

S-phase 5 KVA (Toshiba) (Crossed core type)

Primary, 3300/3150/3000 V

Secondary, 210/105 V

The shape, and dimension indicated in Fig. 2.



Area of the Cover $=0.14\ \mathrm{m^2}$

Area of ①+②+③ $=0.1575\ \mathrm{m^2}$

Total area of the vertical wall surface $=0.53\ \mathrm{m^2}$

Fig. 2

6. Amounts of Heat Generated and Received

(1) **Amount of Heat Generated.** The loss of the transformer used in the present experiment was as follows:

Copper loss, 133 Watts, Core loss, 74 Watts,

Total loss, 207 Watts=178 Kcal/h

(2) **Amount of Heat Received.** According to Table 1, the amount of heat received during a day due to solar radiation was:

$$9.542 \text{ cal/cm}^2 \text{ m} = 5725 \text{ Kcal/m}^2 \text{ day.}$$

Therefore, the amount of heat received on the side in one direction of the transformer was:

$$5725 \times 0.1575 \text{ m}^2 = 901 \text{ Kcal/day,}$$

and the amount of heat received on the cover was:

$$12{,}293 \text{ cal/m}^2 \text{ m} = 7375.8 \text{ Kcal/m}^2 \text{ day}$$

and, therefore;

$$7375.8 \times 0.14 \text{ m}^2 = 1{,}033 \text{ Kcal/day.}$$

The total was; 1,934 Kcal/day.

The maximum amount of heat during the day was received at 4 o'clock in the afternoon. But, for this transformer, the maximum temperature was obtained at about 5 o'clock in the afternoon. Thus, the amount of heat received at 5 o'clock in the afternoon was calculated as follows.

In this case, if the percentage of absorption by a perfect black body is set at 100%, the actual percentage obtained would be roughly 91%, and therefore;

91 Kcal/h=105 watts......from the side of this transformer,

42 Kcal/h=48 watts ......from the cover.

These values pertain to direct insolution. In actuality, above 34% of sky radiation will have to be considered additionally. Then,

$$\left.\begin{array}{l} \text{From the vertical side......} \\ \quad 122 \text{ Kcal/h} = 141 \text{ watts} \\ \text{From the cover ....} \\ \quad 56 \text{ Kcal/h} = 64 \text{ watts} \end{array}\right\} 178 \text{ Kcal/h} = 205 \text{ watts.}$$

Thus, it is known, at 5 o'clock in the afternoon when the maximum temperature is obtained, the transformer is heated by 412 watts, which is the sum of 207 watts, the loss of the transformer, and 205 watts, the amount of heat received due to solar radiation.

7. Experimental Results

(1) **In case of No Load** (with solar radiation). The experimental results were;

Temperature rise of the case .... 10°C

Temperature rise of the oil .... 8°C

Temperature rise of the coil .... 6°C

Thus, the amount of heat necessary for the above-mentioned temperature rise will be calculated to be 121 Kcal. Accordingly, it is seen that about 10% of the heat due to solar radiation is absorbed and the remaineder released. According to the test, the heat of about 15 Kcal/°C h is transmitted from the case to the oil. Because of the temperature difference of 2°C, as indicated above, about 8 hours will be needed for 1°C, which is the average value of the afore-said 2°C and 0°C.

(2) **In case of full load indoors.** The experimental results were;

Temperature rise of the case .... 22°C
Temperature rise of the oil .... 30°C
Temperature rise of the coil .... 45°C

If in this case, the amount of heat diffused (Qr) may be calculated by equation (6) as follows:

Qr=90 Kcal/h=104 watts.

If, in this case, no wind exists, the amount of heat diffused (Qc) due to convection may be calculated by equation (7), as follows:

Qc=82 Kcal/h=96 watts.

Thus, the total becoms 200 watts, which roughly coincides with 207 watts, the transformer loss.

(3) **In case of full load outdoors in cloudy weather.** The experimental results were;

Temperature rise of the case .... 17°C
Temperature rise of the oil .... 29°C
Temperature rise of the coil .... 37°C

In this case;

Qr=68 Kcal/h=79 watts.

Thus, the amount of heat diffused ($Q\omega$) due to wind velocity of 1.5 m/s may be calculated by equation (9), as follows:

$Q\omega$=134.9 Kcal/h=157 watts.

$\therefore \quad Qr+Q\omega$=236 watts.

Thus, the value here is larger than the loss which is 207 watts, by 27 watts, But, sky radiation of about 10 mW/cm^2 will have to be considered even in cloudy weather, and, accordingly, this extent of error is assumed to be a matter of course.

(4) **In case of full load outdoors** (with solar radiation). The experimental results were;

Temperature rise of the case .... 24°C
Temperature rise of the oil .... 31°C
Temperature rise of the coil .... 39°C

In this case, the amount of heat received due to solar radiation was 205 watts as calculated at 5 o'clock in the afternoon when the maximum temperature was obtained for this transformer.

Thus, the total heat; 207+205=412 watts.

In this case, the amount of heat released:

$$Qr=120 \text{ watts}, \qquad Q\omega=222 \text{ watts}$$

$$\text{Total}=342 \text{ watts}.$$

Thus, it is seen that the amount of heating was larger by 70 watts, and that at 5 o'clock in the afternoon, the temperature is assumed to have still been in the course of rising.

Fig. 3—4 show an example of the experiment.

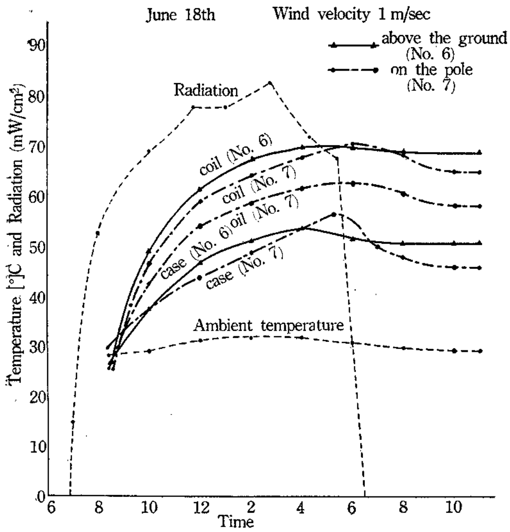


Fig. 3

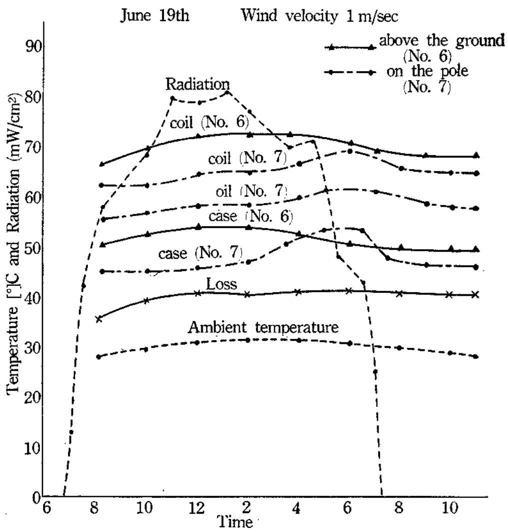


Fig. 4

As the solar radiation is on a gradual decrease, this temperature rise is assumed to cease in a short period of time.

The time of cloudy weather and solar radiation is compared as follows:

	Cloudy	Solar radiation	Temperature difference
Case	17°C	24°C	7°C
Oil	29°C	31°C	2°C
Coil	37°C	39°C	2°C

8. Conclusion

The heat capacity of the transformer, according to equation (5), is represented by:

C_1 for coil and core, C_2 for oil, and C_3 for case and all of these are combinedly represented by C.

Now, if the heat conductivity between the case and outer atmosphere is represented-ly (K), and the amount of heat received due to solar radiation by (Q), the equation below may be obtained:

$$Q=C\frac{d\theta}{dt}+K(\theta-\theta_0) \tag{10}$$

However;

θ ....Temperature due to solar radiation

θ_0 ....Ambient temperature.

The transformer is accompanied by the copper and core loss and the consequent temperature rise. The transformers of various capacities are designed for an approximately identical temperature rise, and, therefore, it is assumed that the temperatuae rise due to solar radiation above is indicated by equation (10).

The solution to this equation will be:

$$\theta-\theta_0=Q/K(1-e^{-k/c\,t}) \tag{11}$$

Again, if; J=solar radiation

A=the area receiving solar radiation

$Q=AJ$.

and, therefore;

$$\theta-\theta_0=\frac{AJ}{K}(1-e^{-k/c\,t}) \tag{12}$$

In this equation, the heat diffusing area of the transformer is proportional to K, while A represents the area where heat is received, and, therefore, A/K will be constant in case the transformer has the case of identical shape. For example, in case of a round-shaped case, not provided with a fin, it becomes roughly:

$$A/K=\frac{1}{\pi}.$$

Thus, in the case of transformers of which the case is of an identical shape, the maximum temperature rise will be just the same.

In case, however, of a transformer with a fin, K will become larger, though A remains unchanged, and, thus, the maximum temperature due to solar radiation will become lower.

If a pole transformer with a relatively small capacity and not provided with a fin, is considered, the value of A, K and C, respectively, will be as indicated in Table 2. Up to 3~15 KVA, the value of A/K will remain roughly unchanged. The value of K/C, if 5 KVA is taken for 100%, will be 129% at 3 KVA, and 85.7% at 15 KVA. This fact indicates that the time needed for temperature rise at 3 KVA is shorter than at 5 KVA, and that such time is longer at 15 KVA. About 8 hours are required at 5 KVA before the maximum temperature is obtained, while, at 3 KVA, a much shorter time is sufficient for obtaining the maximum temperature. At 15 KVA, on the other hand, the maximum

Table 2

capacity	A(m²)	k(m²)	c(kcal/°C)	A/k	k/c
3 KVA	0.247	0.578	9.728	0.427	0.059
5 KVA	0.283	0.667	14.535	0.424	0.046
7.5 KVA	0.319	0.756	16.434	0.423	0.046
10 KVA	0.369	0.873	19.910	0.423	0.044
15 KVA	0.407	0.974	24.625	0.420	0.040

k = Area of heat diffusion. $K \infty k$

temperature is obtained much more slowly.

If it is assumed that the temperature rise due to solar radiation at 5 KVA is 2°C, the rise at 3 KVA will exceed that, while, at 15 KVA the solar radiation will become low before the maximum temperature is obtained, and, eventually, it will become zero, without ever obtaining the maximum temperature all through the day. Namely, it is assumed that the temperature rise due to the solar radiation, if any, remains below 2°C.

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