ENVIRONMENTAL EFFECT ON TEMPERATURE RISE OF TRANSFORMER

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ABSTRACT

All the experimental results based models for the temperature rise prediction of an oil transformer do not completely explain the exact ambient temperature effects on transformer due to empirical nature of formulas. In this paper we have taken into account the semi theoretical approach which leads to explain air properties and relative environmental humidity effects on the temperature rise of oil natural air natural cooled transformers.

This paper covers the research conducted in a series of testing done on distribution transformers regarding temperature rise. We have discussed the ambient effects which are dependant upon relative humidity and natural wind siphon that a transformer surface creates.

The experimental results are also discussed along with the theoretical values to vet the theoretical study. The experiments are done on various transformers on different environmental conditions in a calendar year. The comparison of the theoretical study and the experimental verifications are also discussed in this paper.

The study has evolved that relative humidity as a major environmental component effects temperature rise considerably. The results may help in minimizing the band of predicted temperature rise ranges in contrast to empirical models.

INTRODUCTION

For distribution transformer as a major network component, the actual environmental conditions are of great importance when the design considerations are made. The weather parameters at installation site, like average wind and humidity conditions for whole year in that area, are of most importance in thermal design calculation. Same conditions may vary temperature rise of transformer and if thermal design is not according to the severity of conditions, the temperature rise may increase and life of transformer may fall shorter than expected. Discussed below are the different semi theoretical formulations of heat transfer which may be used by designers for better results. Most important of which are the formulas for severe conditions when moist air surrounds transformers made hermetically sealed with corrugated walls. The complexity of theoretical formulas is out of context of this paper and the oil and inner parameters are not discussed however focus is kept on properties of air and their variation.

LUMPED MODEL FORMULAS COMMONLY USED IN TRANSFORMER HEAT TRANSFER

The main source of temperature rise in a transformer is iron and copper losses from which all the thermal models are started. These losses in the form of heat are transmitted to the oil in transformer and the transformer oil expands and rises above winding, cold oil from cooling fins replaces its position and thus a circle of oil movement starts. The losses in the form of thermal power are dissipated through conduction and convection as given by [1]:

$$P = m_o c_o \frac{d T_o}{dt} + h_o A (T_o - T_{ti}) \qquad (1)$$

Where
P = Total losses in watt.
m_o = Mass of oil in transformer in kg.
c_o = Oil specific heat capacity in J/kgK
h_o = Oil convectional heat transfer coefficient in W/m^{2}K
A = Tank surface area in m^2
T_o = Oil temperature in K
T_{ti} = Tank inner temperature in K
The oil further transmits this energy to tank walls which transmit it by conduction to outer surface of the tank; this expression can be written by:

$$h_o A (T_o - T_{ti}) = \frac{A c_t}{w} (T_{ti} - T_{to}) \qquad (2)$$

Where
c_t = Tank conductive heat transfer coefficient in W/m^{2}K.
T_{to} = Tank exterior temperature in K.
w = Tank wall thickness in meter.
This complete heat is taken by air through convection and the expression can be given by:

$$\frac{A c_t}{w} (T_{ti} - T_{to}) = h_A A (T_{to} - T_A) \qquad (3)$$

Where
h_A = Air convectional heat transfer coefficient in W/m^{2}K
T_A = Ambient temperature in K.
If we combine 1, 2 and 3 then we can assume that in steady state:

$$P = m_o c_o \frac{d T_o}{dt} + h_A A (T_{to} - T_A) \qquad (4)$$

This means that major factors involved in temperature rise of transformer are the mass of oil, surface area of tank or

cooling fins and the convective heat transfer coefficient of air. The mass of oil and surface area are controllable parameter but the convective heat transfer coefficient of air entirely depends upon environmental conditions.
The convective coefficient of air depends on conductive heat transfer coefficient, height of fins and nusselt number as:

$$h_A = \frac{Nu\,k}{L} \tag{5}$$

where:
Nu = a dimensionless number for air called nusselt number.
K = conductive heat transfer coefficient in W/m K.
L = vertical length or height of cooling fin in meter.
The nusselt number and thermal conductivity coefficient are usually taken constants but in actual they are strongly influenced by environmental conditions, air being mixture of gases and vapours is difficult to derive with theoretical formulas so most of its properties are tabulated by scientist after experiments about which the detail is discussed below.

HEAT TRANSFER MECHANISM IN AIR NATURAL COOLED TRANSFORMERS

There are three basic conditions to which a transformer is subjected when it is called as air natural cooled transformer.

1. Natural convection: when velocity of air around transformer is almost zero and the air is assumed to form self circulation around tank body or indoor conditions.
2. Forced natural convection: when ambient air around transformer flows in measurable, influential velocity.
3. Highly humid conditions: when humidity level is more than 50% and in foggy areas.

The calculation of nusselt number for all these conditions can be consulted through various experiments done on vertical flat plate and the concluded results of scientists can be summarized as under.

Natural Convection:

Ambient air at low temperature around transformer fin gains heat from fin and expands, thus its density reduces and a buoyancy force generates to lift it up and move cold air at its place. Thus a natural wind movement starts on the cooling fin surface and a boundary layer of air produces. Up to certain heath of fin, the flow remains laminar and above that height it converts to turbulent flow as shown in fig.1.
Nearly all the natural convection phenomena carry out in completely turbulent or mixed flow boundary layer of air. For such boundary layer, the formula derived for nusselt number calculation is[2]:

$$Nu = C\, Pr^a\, Gr^b \tag{6}$$

Where:
C= constant = 0.1
a = b = 0.33
Pr = Prandtl number depending on ambient (see table 1.)

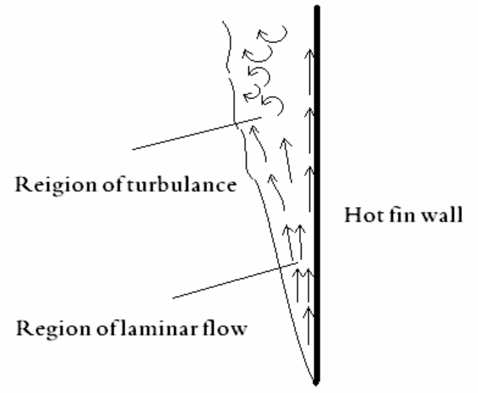

fig. 1 natural convection with mixed flow

Gr = Grashof number
This is a dimensionless number which covers the buoyancy forces and gravitational forces on air molecules. This can be calculated as:

$$Gr = \frac{g\,\beta\,\Delta T\,L^3}{\upsilon^2} \tag{7}$$

Where
g = Gravitational constant
$\Delta T = T_{to} - T_A$
υ = Kinematic viscosity of air (see table 1)
β = Expansion coefficient of air (see table 1)

Forced Natural Convection:

In case if outdoor conditions in tropical or coastal regions, where wind flows in considerable velocity most of the time, the conditions come similar to forced convection where

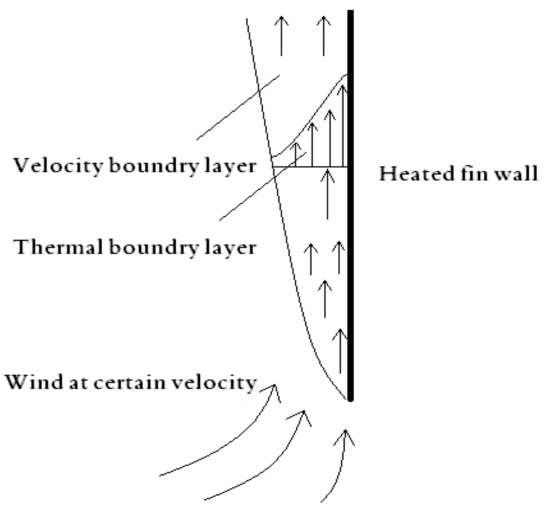

fig.2 Laminar flow forced natural convection

Flow tends to become laminar in the boundary layer as shown in fig. 2. The derived formula for nusselt number calculation [3] for such conditions can be derived to final expression as:

$$Nu = C\, Re^{a}\, Pr^{b} \quad (8)$$

Where:
C = constant = 0.664
a = 0.5
b = 0.33
Re = Reynold's number, a dimensionless set of variables
And

$$Re = \frac{U\, L}{\upsilon} \quad (9)$$

Where:
U = average velocity of ambient air in m/s
Thus in such conditions, nusselt number is influenced greatly by ambient air average velocity.

Highly humid conditions:

Third and most curtail environmental conditions for transformer temperature rise is when installation sites are high humidity areas. The nusselt number calculation in such conditions is in close resemblance of conditions which leads to the expression derived by Chirchill and chu (1975) [3] and is given by:

$$Nu = 0.68 + \frac{0.67\, Ra^{1/4}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{4/9}} \quad (10)$$

Where:
Ra = Rayleigh number

And $$Ra = \frac{g\, \beta\, \Delta T\, L^{3}}{\acute{\alpha}\, \upsilon} \quad (11)$$

Where:
ά = Thermal diffusivity of air (see table 1)
This expression gives us close results for installation sites where the relative humidity value is more than 50% as far as experimental data is observed.
Although the complexity of air and water vapor mixture is more difficult to cover but this expression of nusselt number leads to the value of convective coefficient more near to what is suggested by actual results.

T (K)	ά (m^2/s) x 10^{-5}	β (1/K)	k (W/m-K)	υ (m^2/s) x 10^{-5}	Pr
260	1.705	0.00379	0.02329	1.214	0.712
270	1.824	0.00367	0.024	1.299	0.712
280	1.879	0.00355	0.02477	1.385	0.711
290	2.078	0.00343	0.02544	1.475	0.71
300	2.213	0.003315	0.02623	1.578	0.713
310	2.34	0.0032	0.02684	1.659	0.709
320	2.47	0.0031	0.02753	1.754	0.708
330	2.616	0.003	0.02821	1.851	0.708
340	2.821	0.002915	0.02888	1.951	0.707
350	2.931	0.00283	0.02984	2.073	0.707

Table 1. Air properties at ambient temperature range [3]

EXPERIMENTAL VERIFICATIONS

Experiments were performed on different transformers in different environmental conditions. Here we present the results for two transformers, one of 200 kVA and other of 400 kVA. Both were tested twice for temperature rise testing in variable environment conditions. The results are shown here:

200 kVA Transformer:

Transformer details:
Fins height = L = 0.6 m
Cooling area = A = 16.84 m^2
Losses = 3124 Watt
Mass of oil = m = 224 kg
Experiment 1 detail:
Conditions: Indoor
Average humidity = 44%
Average ambient temperature = 304 K
Theoretical temperature rise:
Using equations (4), (5), (6), (7) and table 1.
Maximum temperature at tank = 310.7 K
Experimental value:
Top oil temperature rise = 309.93
Difference = 0.77 K

Experiment 2 detail:
Conditions: outdoor
Average humidity = 70 %
Average ambient temperature: 306 K
Theoretical temperature rise:
Using equations (4), (5), (10) and (11)
Maximum temperature at tank = 312.84
Experimental value:
Top oil temperature rise = 314.37
Difference = 1.53 K

400 kVA transformer:

Trnsformer detail :
Fins height = L = 0.8 m
Cooling area = A = 25.4 m^2
Losses = P = 5435 Watt
Mass of oil = m = 465.5 kg

Experiment 1 detail:
Conditions: outdoor mixed
Average humidity = 57%
Average Wind speed = 2.85 m/s
Average ambient temperature = 297 K
Theoretical temperature rise:
Using equations (5), (8), (9), and table 1.
Value of h = 7.389
Using equations (5), (10), (11), and table 1.
Value of h = 3.577
Since wind speed was considerable for first 4 hours of the experiment of 8 hours and it was nearly calm for the

remaining half, we need to take average of both values to find resemblance to environmental conditions.
h_{av} = 5.483 Watt/m^2 K
Using equation (4)
Maximum temperature at tank = 304.48 K
Experimental value:
Top oil temperature rise = 304.63 K
Difference = 0.15 K

Experiment 2 details:
Conditions: outdoor mixed
Average humidity = 42 %
Average Wind speed = 1.22 m/s
Average ambient temperature: 301.5 K
Theoretical temperature rise:
Using equations (5), (6), (7) and table 1.
Value of h = 4.06
Using equations (5), (8), (9) and table 1.
Value of h = 4.83
Since conditions were mixed for natural and forced convection conditions, we have to take average of both values for h.
h_{av} = 4.45 Watt/m^2 K
Using equation (4)
Maximum temperature at tank = 309.9 K
Experimental value:
Top oil temperature rise = 310.17 K
Difference = 0.27 K

CONCLUSION

Temperature rise of a transformer in operation in open environment may not always be the same as concluded in controlled environment. Wind speed and humidity at installation sites are of prior importance for temperature rise design considerations of a transformer. Wind is good for temperature decrement and humidity may be adverse. Also the parameter of fin design which affects the temperature rise the most is the height of the fin. Study also reveals that the understanding of designers that area of fin height below the bottom of coil is ineffective area is also proved wrong as formulas suggest that the height of the fin above certain limit starts becoming less effective due to behaviour of boundary layer. Experiments revealed that high humidity with calm environment may increase the temperature rise of distribution transformers up to 5 degrees so the transformers designed at edge with paper class of 105°C limit and temperature rise design margin of 5 degree may cause loss of life if installed at a site of humid and calm environment. Study has also suggested that before designing of transformer, the average climate conditions of site must be considered for temperature rise of transformer.

Acknowledgments:
We would like to say thanks to Mr. Sadiq monir, Senior Manager Design at PEL for his support and Dr. Asgar Saqib and Mr. Sufian Adeel from UET Lahore for their valuable suggestions.

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