Thermal designing and building transformers for use with viscous fluids

1. Introduction and history

Before the 1970s, transformers that needed to be fire resistant used dielectric fluids that contained chlorinated chemicals. These fluids were generally called PCB (poly chlorinated biphenyl) or "askerel" fluids. Because of the poor health and environmental characteristics of these PCB fluids, they were discontinued worldwide in the 1970s and replaced with newer types of fire resistant fluids.

ABSTRACT

Since the 1970s, transformers have used special fire resistant fluids that are often more viscous than standard transformer oils. This article looks at the different types of fire resistant oils that have been used, and the changes in transformer cooling design that have been made to accommodate their higher viscosity.

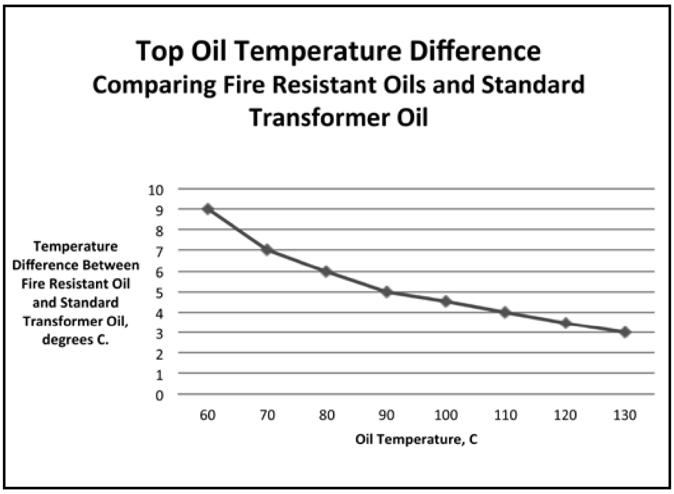
Keywords

transformer cooling, fire resistant oils

These fluids usually relied on a high molecular weight to give them a low vapor pressure and therefore, fire resistance. Their high molecular weight also made these fluids more viscous than standard mineral oil. Transformer cooling designs had to be reworked in order to stay within standard temperature ranges when using these new fluids. When those new fire resistant fluids were introduced for use in transformers, manufacturers attempted to apply the fluids in transformers designed with rules that had been developed to use conventional transformer oil (like PCB). More often than not, the rules for transformer cooling with standard transformer oil had been developed over years of trial and error, and were specific to each design and brand of transformer. Temperature rise tests show that the higher fluid viscosity had little effect on winding temperature or top fluid temperature rises. However, temperature rise tests on larger transformers indicated that the top oil temperatures of transformers filled with these fluids ran 4 to 6 degrees warmer than the same transformer designs filled with conventional transformer oils. Figure 1. shows the increase in operating temperature between a fire resistant fluid (Alpha-1 Fluid from DSI Ventures, Inc.) and standard mineral transformer oil (in this paper, "standard transformer oil" refers to mineral oil per ASTM Standard D3487 or IEC Standard 60296)

In early applications of these fire resistant fluids, transformer manufacturers lowered the guaranteed kVA rating of transformers to compensate for increased temperature rises experienced during tests. Reductions in ratings varied from 0 for small transformers below 50 kVA to approximately 15% for a silicone fluid-filled transformer rated 1500 kVA, convection-cooled (ONAN) unit. Additional fans were generally used to meet the forced-air cooled (ONAF) ratings. Manufacturers recognised that, in order to comply with guaranteed temperature rises of standard ratings, that cooling designs needed to be modified when applied to transformers filled with fire resistant fluids.

Table 1: Temperature differential when using fire resistant oil



The physical features of a transformer that have to be taken into account when predicting winding temperature and top oil temperature were derived in the 1930s and 1940s. They are the coil dimensions, tank dimensions, coil duct dimensions, external cooling equipment arrangements and dimensions, heat flux densities of the heat dissipation surfaces in the coils, the tank, and the external cooling equipment. Most manufacturers' thermal calculation methods evolved from equations (2) (3) and (4) relating heat flux rate and temperature rises for oil filled transformer as proposed by Montsinger [1].

Equation (2) was derived from the Stefan-Boltzman equation governing radiative heat transfer:

$$P = e\,\sigma\,A(T_2^4 - T_1^4) \qquad (1)$$

Where P = radiation loss rate per unit of time (watts)
e = emissivity of the radiating material; a constant unique to the material and < 1 for all real world materials.
σ = the Stefan constant, 5.67 x 10-8 W/m·K

Transformers designed for standard insulating oils require changes in cooling design when they are used with viscous fluids.

A = the area of the radiative surface
T_1 and T_2 are the absolute temperatures of the radiator and of the surroundings, respectively, in Kelvin.

Montsinger [1] rearranged and simplified the Stefan-Boltzman equation, solving for the area of radiative surface area needed equation (2).

$$w_r = KrE(T_2^4 - T_1^4) \qquad (2)$$

w_r = heat dissipation per unit of surface for radiation
K = a constant, normally empirically derived
E = emissivity of the heat transfer surface, a constant specific to the material and < 1 for non-ideal (real life) materials.
T_2 and T_1 = higher and lower temperatures (temperature differential for heat transfer), measured in Kelvin (absolute temperature)

The heat flux density for heat transfer rates by convection from external cooling surfaces (tank walls and radiator was given by equation (4). This equation was derived from the general convective heat transfer relationship:

$$q = h_c A \;\Delta\theta \qquad (3)$$

where q=heat transferred per unit time (Watts)
where h_c = the convective heat transfer coefficient in W/(m²·K)
θ = temperature in degrees C.

Rearanging equation (3) to solve for heat transferred per unit of area:

$$w_c = K_c\,(\Delta\theta_c) \qquad (4)$$

w_c = heat dissipation per unit of surface for convection
K_c = a constant, normally empirically derived, which incorporates the convective heat transfer coefficient and heat transfer inefficiencies found in real life

Rules for transformer cooling design have traditionally varied between manufacturers, and often developed through trial and error.

Equation (5) was proposed to determine the temperature rise of conductors as related to heat flux density between heated surfaces and transformer oil.

$$\Delta\theta = K_f w_f{}^{n} \mu^{n'} \qquad (5)$$

$$hL/k = F(\rho^2 g \beta C_p L^3 \theta / \mu k) \qquad (6)$$

This equation relates the properties of the cooling medium (oil or air as appropriate) by changing the appropriate fluid properties to constants. Most transformer manufacturers had developed design rules modifying these equations with empirically developed correction factors, which have been simplified for use with transformer oil so that the relationship with fluid properties were not used.

h = height of coil ducts inside the transformer, mm
L = length of coil ducts, mm
F = constant derived for each fluid that simplified specific fluid characteristics and interaction between fluid and cooling duct walls. Starting with F=1, the constant was derived by iterative trial and error until the calculated values matched experimental values for winding temperature rise.
ρ = density (g/cm3)
C_p = specific heat (J/K)
k = thermal conductivity ($W/(m^2 \cdot K)$)
β = coefficient of thermal expansion ($°C^{-1}$)
μ = absolute viscosity (Pa·s)
g = gravity constant, 9.8 m/s^2

Tests on transformers filled with fire resistant fluids (both fire resistant hydrocarbons and silicone fluids) indicated that these empirically developed equations needed to be modified to compensate for the differences in fluid characteristics. In the case of the fire resistant hydrocarbons, the principal difference was viscosity. In the case of silicone fluid, there were significant differences in specific heat, thermal conductivity, coefficient of thermal expansion and specific gravity.

Table 2. compares the physical and thermodynamic characteristics of currently available fluids with that of standard (American Standard ASTM D3487) transformer oil:

Table 2. Characteristics of currently available alternative (fire resistant) transformer insulating oils:

Fluid type Standard D3487 transformer oil	ASTM hydrocarbon PAO	Synthetic petroleum	Fire resistant fluid	Silicone ester	Natural ester	Synthetic
Brand Name		Alpha-1 Fluid*	Beta Fluid	DC561**	Envirotemp FR3	Envirotemp 200***
Fire point ASTM D92, °C.	145	308	306	343	330	310
Kinematic viscosity @ 40 C. ASTM D445, m^2/s.	12	68	105	113	33	22
Kinematic viscosity @ 100 C. ASTM D445, m^2/s.	3.0	8.5	11.1	15.0	8.0	4.6
Pour point, D97, °C.	-45	-55	-24	-24	-21	-50
Specific gravity kg/dm^3	0.87	0.82	0.87	0.91	0.92	0.97
Coefficient of thermal expansion units/C	0.00072	0.00060	0.00072	0.00103	0.00072	0.00072
Specific heat capacity, J/kg-K (50 C)	1.86	2.23	2.29	1.51	2.10	1.88
Thermal conductivity, W/(m·K) (50 C)	0.126	0158	0.152	0.151	0.167	0.150

* Alpha-1 Fluid and Beta Fluid are Trademarks of DSI Ventures, Inc. ** DC561 is a Trademark of Dow Corning, Inc.
*** Envirotemp FR3 and Envirotemp 200 are Trademarks of Cargill Corporation.

Depending on the size of the transformer and the fluid used, transformers using fire resistant fluids can require up to 15% more heat transfer surface than the same unit with standard mineral oil.

Transformer design engineers identified those fluid characteristics whose interaction with the transformers' physical characteristics affected the temperature rise of a transformer. These fluid physical properties identified were absolute viscosity (μ, Pa·s), density (ρ, g/cm³), specific heat (J/K), thermal conductivity (k, W/(m·K)), and coefficient of thermal expansion (β, $°C^{-1}$). Relationships between these fluid properties, a transformer's physical characteristics, and temperature rises of oil ducts, were presented in various studies [2], [3].

2. Transformer design modifications

Today's transformer design engineers have at their disposal modern transformer design tools to help them model and predict fluid flow and heat transfer patterns inside transformers. Use of these heat transfer predictions can optimise cooling designs, eliminating points of inefficiency, low fluid flow, hot spots and other problem areas encountered in transformer cooling.

Unfortunately, these tools are not used by many transformer manufacturers because of cost, lack of expertise or lack of time and manpower. Smaller manufacturers more often rely on "rules of thumb" when designing or modifying transformer cooling systems. We shall look at some of these time-tested rules in the sections below. Even engineers with computerised models at their disposal can benefit from a thorough understanding of design changes that have worked in the past, and why.

Historically, there were few standard transformer design procedures to modify. Most transformer temperature design routines were developed empirically and then modified to conform to test results so changes in these rules are made in the same way. The following guidelines have been successfully used to develop cooling designs for transformers using new fire-resistant fluids.

3. External cooling

The higher viscosity of a fire resistant fluid slows down the fluid's flow velocity in a transformer cooling circuit, thereby causing an increase in the top oil temperature. Cooling can be enhanced by increasing internal or external heat transfer surface area or by increasing the fluid's flow velocity. It is usually easier and less expensive to make changes in a transformer's external cooling surface by adding extra radiators than it is to change internal cooling duct design. Very often, adding an extra bank of radiators is all that is required to use fire resistant fluids with standard oil designs, particularly for smaller transformers. The amount of additional cooling surface required would be in proportion to the anticipated percentage increase in top fluid temperature. This is usually determined by doing factory heat runs with the more viscous fluid in standard transformer oil designs.

Since the amount of heat generated by the core and coils is the same (neglecting temperature effects on resistive losses), the same amount of heat must be dissipated from the external surfaces for both standard transformer oil and fire resistant fluid.

Since the total heat dissipated from the external surfaces to the air is unaffected by the fluid property changes, equation (6) may be used iteratively to determine the additional area required to reduce the average temperature rise. Put simply, it says that the external heat transfer surface required for a viscous fluid is a factor of

$$w_{\text{fire resistant}} = k_E A_{\text{eff}} \left((\Theta_{\text{fire resistant tf}} - \Theta_{\text{fire resistant bf}})/2 - \Theta_{\text{amb}} \right)^n \quad (7)$$

The value ($\Theta_{\text{fire resistant-tf}}$) would have to be reduced according to the anticipated temperature increase of the winding, which is also a function of the coil ducting practices used.

4. Coil design changes

The increase in viscosity of fire resistant fluids over standard transformer oil is a major factor causing the increase in the average winding rise and top oil temperature experienced when changing to a fire resistant fluid. The increase in top oil temperature caused by the change to a higher viscosity fluid may be minimised by changing the coil design such that the quantity of fluid flowing through the coil is approximately the same as it was for standard transformer oil. This may be accomplished by either increasing the coil duct sizes or increasing the number of ducts or a combination of both. Guidelines for varying the number of ducts and duct thickness are given in [1].

Experience has indicated that, in convectively cooled (ONAN) transformers, unacceptable top fluid temperatures rises may occur if ducts smaller than 4.5 mm are used for fluids that are more viscous than standard transformer oil. Figure 2 shows a comparison of temperature rises in the ducts with viscous and standard transformer oil. Thinner ducts may be acceptable for smaller transformers with smaller top to bottom temperature differentials, however, for larger, taller transformers, the increased viscosity of the colder oil at the bottom coil duct opening may cause an unacceptable increase in resistance to fluid flow. Satisfactory winding temperature rises less than 10°C have been obtained with internal duct thickness of 6.35 mm for coils up to 914 mm tall. Ducts sizes have been increased to 9.5 mm for taller coils with higher heat flux limited by available space for adding ducts.

Experience with fire resistant fluids in convection-cooled (ONAN) transformers with disc coils has been limited, so these guidelines should be used with layer windings only. However, satisfactory results have been reported with fire resistant fluids in forced-oil (OFAF) rated transformer with both disc and layer windings. In order to achieve satisfactory cooling results with larger transformers using disc coils require appropriate modifications to pumps, cooling tubes, and coil ducts to compensate for the increased flow resistance of the fire resistant fluid.

Taller transformers usually require more changes, due to the longer internal cooling duct path.

5. Effect of transformer size

Smaller transformer ratings are less affected than larger transformer's by the differences in fluid viscosity properties of fire resistant and conventional transformer oil due to the following.

1. Small transformers of 25 kVA and less have more tank cooling surface than is required to maintain the top oil below guaranteed values. Therefore a slight increase in top oil temperature will usually not exceed the guaranteed temperature rise.
2. The increase in viscosity has a greater effect on heat transfer in small coil ducts than it does on open surfaces such as the outer coil surface or the outer tank wall. Since the outer coil surface/ tank perimeter is a greater portion of the total cooling surface than coil cooling area/external cooling panels, the increase in viscosity has less effect on small transformer.
3. The total heat (W_t) dissipated by the tank's external surfaces is the sum of the heat dissipated by convection (W_c) plus the heat dissipated by radiation (W_r). Radiative heat dissipation is often only half of the total heat dissipated on a small transformer and decrease to a negligible percentage of total cooling on larger transformers. Since the increase in viscosity has a greater effect on the convection cooling, larger transformers will see a greater change in top fluid temperatures.

6. Larger transformers and fire resistant fluids

For transformers larger than 500 kVA, a combination of more internal cooling ducts and more external radiators is usually needed to maintain proper cooling when using fire resistant fluids. Transformers rated 750 kVA and larger often have thermostatically controlled oil pumps (ONAN/ONAF), which places additional demands on improved ducting of the coils. Both larger duct sizes and increased quantities of cooling ducts are generally needed to improve the fluid flow and reduce the temperature differential between the top and bottom fluid temperatures to an acceptable average surface temperature to allow effective use of external cooling radiators. An additional number of external radiators with shorter heights is sometimes used in combination with an increased number of coil ducts to maintain a suitable average oil temperature.

Factory heat run testing should be employed to determine the empirical constants appropriate for a particular transformer designs. Test procedures originally developed to determine these empirical factors for fire resistant fluid have been refined and developed into an IEEE recommended practice [4] for verifying a transformer's thermal performance.

Conclusion

Present technology for determining the temperature rise of transformers is based on empirical relationships, relating the fluid characteristics, heat input, temperature rises, and dimensions of appropriate heating or cooling surfaces. Original design rules for use with viscous fluids were developed by trial and error for mineral oil cooled transformers, with fluid properties normally reduced to "constants" in the equations. When using fire resistant fluids, any changes in transformer design rules required the same type of reiterative empirical testing and modification of the cooling design based on the results of these tests. Design changes made in this way must be verified with tests to assure that winding temperature and top fluid temperature guarantees are met. The changes necessary are dependent on many factors, different and proprietary with each manufacturer. These factors would include:

(1) present thermal design rules used for oil filled transformers
(2) types and properties of insulating materials, especially the oil duct materials
(3) differences in coil types and construction
(4) shapes and dimensions of external cooling surfaces, particularly the oil space in external cooling tubes or panels.

Economic factors such as cost of cooling equipment, cost of conductor materials, and costs of fluids to a particular manufacturer, would also have a significant effect on the final design rules selected.

Symbols

C_p = specific heat (J/K)
k = thermal conductivity (W/m·K)
K = experimentally determined constant
w = heat dissipation per unit surface (W/cm^2)
W = total heat dissipated (watts)
β = coefficient of thermal expansion (°C^{-1})
Θ = temperature (°C)
μ = absolute viscosity (Pa·s)
ρ = density (g/cm^3)

Subscripts

amb = ambient temperature of surrounding cooling media
bf = temperature of oil/fluid near the bottom of tank.
c = convection
eff = effective surface area for dissipating heat
E = emissivity of surface
f = fluid
fire resistant = the more viscous insulating oil
n = exponent relating temperature rise to heat dissipation
o = oil – standard mineral transformer oil
r = radiation
tf = top fluid temperature
T_1, T_2 = absolute temperatures K

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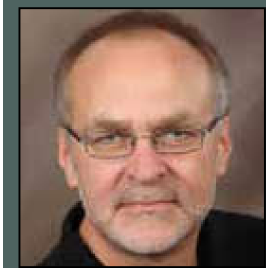
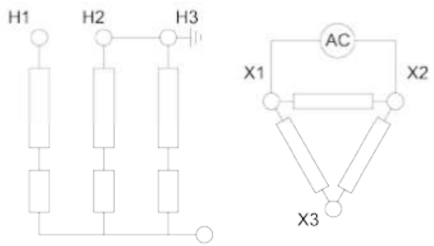
Author



David W. Sundin, Ph.D. is a technical and management consultant with more than 30 years experience with heat transfer, transformer oil manufacturing and testing, and business ownership. He is active in industry standards groups such as IEEE, ASTM and CIGRE. In addition to electrical insulating oils, Dr. Sundin consults with heat transfer fluids, synthetic and biodegradable lubricants, and recycling technologies. Currently owner of Ambit Technical Consulting, Dr. Sundin can be reached through davidsundin.net or his Linkedin profile.

Correction

Due to a reader's question about Figure 3a from the paper „Voltage stresses on solid-liquid insulation of Large Power Transformers", Transformers Magazine Vol. 1, Issue 1, April 2014; the author has corrected test circuit scheme for single-phase induced voltage test:



"Figure 3: Single-phase induced voltage test in a wye-delta transformer"