Efficient factory drying of solid insulation to remove moisture is a critical step for deceleration of ageing and sizing the core-coil assembly before oil impregnation

Moisture dynamics during pressboard drying

A study of moisture dynamics during factory drying of spacers stack

ABSTRACT

Factory drying of transformer insulation is performed to remove excess moisture from the insulation, which delays ageing and helps in sizing the core-coil assembly before oil impregnation. The rate of drying and cycle time depends on the nature and thickness of the material, temperature and pressure level within the drying chamber, as well as airflow and relative humidity of air, thus making it difficult to obtain universal methodologies for all insulation materials. This paper attempts to explore moisture dynamics of insulation stack (pressboard) that shows significant involvement in height reduction. The article studies the possibility of shorter drying cycle, and the influence that nature and thickness of the material might have on it.

KEYWORDS

transformer insulation, drying, moisture, dynamics, drying rate

1. Introduction

Efficient factory drying of solid insulation to remove excess moisture is a critical step during processing and resizing of core-coil assembly for reliable operation and optimum performance throughout the service life of transformer [1]. Core-coil is defined as the assembly containing the active part of a transformer, i.e. magnetic core mounted with conducting coils properly insulated using Kraft/crepe paper and separated from each other using pressboard stack, as shown in Fig.1. Paper and pressboard are the main components in insulating a core-coil assembly and are cellulose-based components with a natural affinity towards water (moisture). This makes the insulation material "hygroscopic" so that it absorbs moisture easily from the oil and it is related to ambient temperature, thereby increasing the overall volume of core-coil assembly.

Solid material properties such as porosity, thickness and compression strength define moisture retention and visco-elastic behaviour of pressboard spacers, which show a significant role during coil sizing [2]. However, apart from

Figure 1. Lab scale model of typical core-coil assembly in a drying chamber

material properties, rate of drying depends heavily on drying conditions, i.e. temperature and pressure, nature of the drying media, velocity of the drying media and relative humidity. Forthcoming chapters discuss the typical drying technique for transformer insulation stack, theoretical basis of the study, experimental investigations and mathematical evaluation of the proposed hypothesis.

Apart from material properties, rate of drying depends heavily on drying conditions, i.e. temperature and pressure, nature and velocity of the drying media, and relative humidity

2. Drying of transformer insulation

Cellulose-based paper and pressboard occupy large volumes in conventional transformer core-coil assembly in the form of wrapping paper, spacer stack, etc. These materials have a natural tendency to absorb water from the atmosphere at the manufacturing stage, making it vulnerable to oxidative, pyrolytic and hydrolytic degradation. Drying process removes excess moisture from solid insulation by heating and vaporizing the moisture, thus leading to a significant weight and height reduction of the core-coil assembly. The following subsections discuss state-of-the-art techniques of factory drying of transformer insulation.

2.1 Hot air and vacuum drying

Typical drying-out process involves heating the core-coil assembly at a temperature of 85-120 °C by circulating hot air and applying vacuum to remove moisture from the insulation prior to oil impregnation and further processing. During the circulation of hot air, moisture drives out from bulk of solid and accumulates within the surrounding chamber, thus decreasing the rate of drying and increasing the relative humidity of internal air. Vacuum allows evacuation of the moist internal air and restricts temperature elevation, thus making it possible to avoid heat-induced damages in physical and chemical properties of insulation. This operation is strictly limited to small transformers, but longer drying cycle times and temperature irregularities increase the risk of unwanted humidification. In order to overcome this problem, Vapour Phase Drying (VPD) is employed.

2.2 Vapour Phase Drying (VPD)

Vapour Phase Drying (VPD) is a highly popular method used in factory drying and sizing of core-coil assembly and is similar to the conventional vacuum drying. Introduction of a drying fluid (alcohol-based spirit) in the heating chamber in the vapour phase at a temperature of 130 °C and extremely low-pressure levels (0.2-0.5 mbar) allows the fluid to attain thermal equilibrium with the core-coil assembly. At this stage, the fluid along with the moist air is pumped out of the system leaving a relatively "dry" insulation. VPD is more efficient and less time-consuming than vacuum drying, but is only required by large oil-immersed power transformer.

3. Problem formulation

This article studies the moisture dynamics during hot-air drying of insulation stack without applying vacuum, due to restriction of the sample size. Table 1 compiles the specifications of the insulation material studied and properties of air (drying media) at 110 °C.

Table 1. Technical specifications of the materials used and some calculated values

Property	Pressboard (IEC 60641)	Property	Air
Density (kg/m³)	1150	Density (kg/m³)	1.202
Thickness (mm)	1.5	Air velocity (m/s)	3.5
Total height of stack (m)	0.077	Latent heat of vaporization (kJ/kg)	2465.56
Tensile strength (N/m)	94.1	Specific heat (kJ/kg K)	1.006
Initial moisture content (% dry basis)	8.011	Dynamic viscosity of dry air (10^{-5} kg/m s)	2.234
Final moisture content (% dry basis)	0.8	Diffusivity of dry air calculated at 110 °C (10^{-6} m²/s)	35.9
Critical moisture content (% dry basis)	4.5	Convective heat transfer coefficient of air (W/m²K)	25.65

Vapour phase drying is a highly popular method used in factory drying and sizing of core-coil assembly and is similar to the conventional vacuum drying

4. Experimental evaluation

Fig. 1 shows the scale-down model of a core-coil assembly studied for optimizing drying times to give a clear idea of the spacer materials and its location within the assembly. Two major graphs plotted using the experimental data are "Drying curve" and "Moisture retention curve", respectively. The sole purpose of these curves was to justify the moisture dynamics during drying and determination of critical and equilibrium moisture contents that are highly required for calculating drying cycle time, as discussed in the next segment.

Fig. 2 represents the drying curve during initial heating cycle and provides a correlation between percentage total moisture and rate of drying. Rate of drying is the rate of change of moisture concentration in pressboard (measured as a function of weight loss) over time and for a given area, and therefore has the unit kg/m^2s. The drying curve comprises of three different sections and the total drying time (t) required for an effective moisture removal is comprised of these stages, namely warming-up, constant-rate and falling-rate periods, respectively, while Fig. 3 represents the moisture retention and removal with respect to time following the drying mechanism.

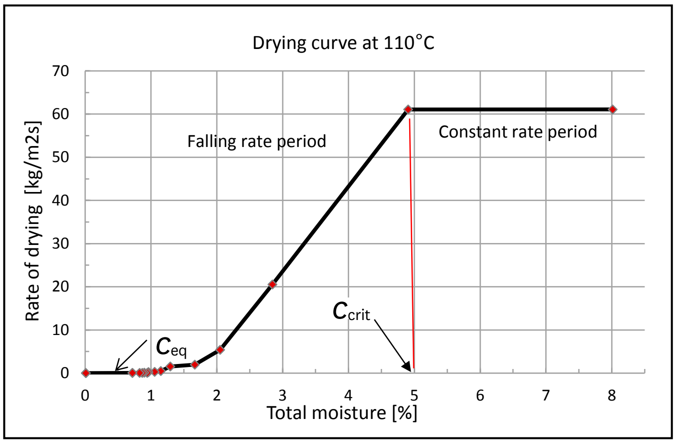

Figure 2. Drying curve during initial heating of the pressboard stack

Warming-up time is a small period when the material starts heating up from the initial temperature to the wet bulb temperature. In this case, the moisture evaporates from the surface of the material, thus delaying the overall heating of the material causing a decrease in moisture concentrations.

Constant-rate period is the phase where the temperature of the material is same as the wet bulb temperature and the difference in mass fraction of moisture in air and at the surface boundary acts as driving force to allow moisture to evaporate in the drying

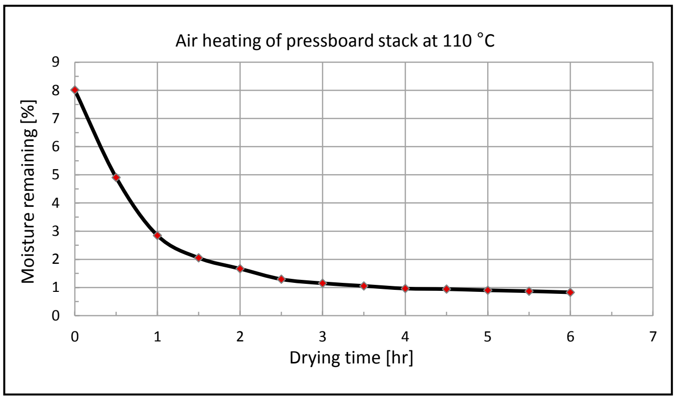

Figure 3. Moisture remaining in the pressboard stack (consolidated) over time

media. Constant-rate period ends when the moisture first drops marking the critical moisture content (C_{crit}) and the beginning of the falling-rate period.

Falling-rate period begins when the material achieves critical moisture and continues until the material reaches the equilibrium moisture content (C_{eq}). Theoretically, equilibrium moisture content should approach zero for any non-hygroscopic material, however in our case, it dropped to 0.008 (percentage moisture on dry weight basis) because of the hygroscopic nature of the pressboard.

5. Mathematical modelling

Drying takes place by movement of water vapour from saturated surface through a stagnant air film. During isothermal heating, the rate of drying at the constant-rate period is dependent on heat and mass transfer phenomenon and this phase continues until the critical moisture content is reached, after which the drying rate begins to fall [4,5]. Equations (1) and (2) represent the rate of the mass flow and heat transfer, respectively, during the constant rate period:

$$\partial C/\partial t = K_s \cdot A \cdot (H_s - H_a) \quad (1)$$

$$\partial Q/\partial t = (h \cdot A/\lambda) \cdot (T_a - T_s) \quad (2)$$

Considering the rate of heat and mass transfer is the same at equilibrium condition and using the finite approximation method, a reasonable solution to demonstrate the time (t_c) required by a material to achieve the constant-rate period is derived as follows:

$$t_c = (\rho L \lambda / h) \cdot [(C_i - C_{crit})/(T_a - T_s)] \quad (3)$$

During the falling-rate period, the drying rate slowly decreases until it approaches zero at the equilibrium moisture content (i.e.

The total drying time required for an effective moisture removal is comprised of three stages – the warming-up, constant-rate and falling-rate periods, respectively

when the material comes to equilibrium with the drying air), and is satisfied by Fick's second law for unsteady state diffusion [4, 5]:

$$\partial C/\partial t = D\cdot(\partial^2 C/\partial x^2) \quad (4)$$

Finite element approximation for time dependent boundary conditions applicable over concentration limits yields a solution for (4), which is expressed as follows [5]:

$$t_f = (\rho L\lambda/h)(C_i - C_{eq})\ ln\ (C_i - C_{eq}) \quad (5)$$

$$(T - T_s) \qquad (C_f - C_{eq}) \quad (6)$$

Where:
$\partial C/\partial t$ = mass flow rate (drying rate) (kg/m^2·s)
$\partial Q/\partial t$ = rate of heat transfer (W)
K_s = mass transfer coefficient (m^2/s)
h = heat transfer coefficient (W/m^2·K)
A = surface area available for drying (m^2)
H_s = humidity at surface (kg moisture/kg air)
H_a = humidity of air (kg moisture/kg air)
T = dry air temperature (°C)
T_a = average dry-bulb temperature of drying air (°C)
T_s = average wet-bulb temperature of drying air (°C)
D = diffusivity of moisture in air from insulation stack (m^2/s)
C_f = final moisture content (% dry basis or kg water/kg of solid)
C_i = initial moisture content (% dry basis or kg water/kg of solid)
ρ = density of pressboard (kg/m^3)
λ = latent heat of pressboard (kJ/kg)
L = total height of insulation stack (m)

It is evident from the observations above that the two necessary conditions required to form boundary value estimations are critical (C_{crit}) and equilibrium (C_{eq}) moisture, respectively, which can only be determined experimentally.

Equilibrium moisture content is the moisture within insulation stack when the material is almost in equilibrium with the drying air, whereas critical moisture content is the moisture in insulation stack when the rate of drying begins to fall

Conclusion

According to calculation (5), the theoretical drying time required for removing initial moisture from 8.011 % to 0.5 % for a stack of 50 non-oil impregnated pressboards with 1.5 mm thickness each is approximately 5.39 hours, while the actual time was approximately 6 hours. The aim of this paper was to study drying cycle time for pre-compressed pressboards that play a significant role in coil sizing. The moisture migration was observed using air heating only for the sake of simplification. If sample size increases, drying time should not change provided the nature, thickness and geometry of material remains the same. Equations are used to explain our hypothesis. Undoubtedly, vacuum heating is another effective way to dry out insulation materials, but due to restrictions in our system, the study focuses on drying time with respect to initial moisture content, thickness of the pressboard, air flow, and temperature and pressure conditions. In our case, the pressboard stack was very small and therefore vacuum drying was not studied. Further investigations are required to understand the effect of such drying times on oil-impregnated materials of similar specifications and their behaviour during moisture removal.

Bibliography

[1] S Raetzke, M Koch, M Anglhuber, *Monitoring the Drying Process of Power Transformers Using Dielectric Response Analysis*, white paper, OMNICRON Electronics.

[2] R Villarroel, D F. García, B. García, J. C. Burgos, *Comparison of the Drying times for Kraft Paper and Pressboard in Transformer Factory Drying*, XX IEEE International Conference on Electrical Machines (ICEM), pp. 1233-1237, 2012.

[3] A S. Asem, A F. Howe, *Drying of Power Transformer Insulation, IEE Proceedings C* (Generation, Transmission and Distribution), vol. 129, no. 5, pp. 228-232, 1982.

[4] A Mujumdar, S. Devahastin, *Fundamental principles of drying*, Exergex, Brossard, Canada, 2000.

[5] W McCabe, J Smith, P Harriott, *Unit Operations of Chemical Engineering*, McGraw Hill, 5th Edition, 1993.

Authors

Sruti Chakraborty is currently pursuing a Ph.D in Chemical Engineering at Malaviya National Institute of Technology (MNIT), Jaipur, India. Before joining the organization she worked with Global R&D, Crompton Greaves Ltd., Mumbai, India as a research intern. Her interests include condition monitoring of transformers, moisture dynamics, insulation materials, mathematical modelling and CFD.

Rahul Zambare is currently pursuing a Ph.D in Chemical Engineering at the Institute of Chemical Technology (ICT), Mumbai, India. He has previously worked at Global R&D, Crompton Greaves Ltd., Mumbai as a research intern. Currently, his areas of interest include membrane separations, sustainable development, drying operations, etc.

Sushil E Chaudhari is a Senior Manager – Technology with Crompton Greaves Ltd, Mumbai, India since 2007. His areas of interest include liquid dielectrics, new manufacturing process development and existing process enhancement, as well as condition monitoring and diagnostics of power transformers and reactors. He is an active member of CIGRE working group and IEEE reviewer. He is a holder of 17 Indian patents and author of 11 scientific publications.