

ABSTRACT

Vapor phase drying is the most effective method for drying transformer insulation in a manufacturing setting. The process does not lend itself well to transformer drying in the field for a variety of reasons, including the difficulty of removing residual kerosene which can cause a potential change in transformer oil flash point. Several techniques are available for transformer insulation drying in both the field and in manufacturing. Vapor phase drying as part of transformer manufacturing is discussed in this paper.

KEYWORDS

Vapor phase, transformer drying, vacuum chamber, VPD

Vapor phase transformer drying – Part I

Vapor phase drying as part of transformer manufacturing process

Photo courtesy of Končar D&ST, Zagreb, Croatia

Introduction

Depending on the voltage class, it is desirable to suppress the water content of cellulosic-based materials to <0.5 % and even as low as 0.1 % (by weight) prior to shipment. Cellulosic Kraft materials (see Figure 1) such as high density pressboard, papers, tapes, crepe tubes and spacers are used in the paper/oil insulation system of the transformer. These are used to support windings and leads as well as to maintain dielectric clearances.

These materials are often provided by the supplier to the transformer manufacturer with a moisture content of approximately 5 %. Because these materials are hygroscopic, they will take on some additional moisture through exposure to humid air during the manufacturing process. Efficient suppression of the moisture content from a starting point of >5 % to less than 0.5 % may involve the removal of many litres of water from the solid insulation during vapor phase drying.

A major consideration when comparing drying techniques is the time required to perform a complete, uniform drying of the entirety of the insulation system. Faster drying times reduce this step as a bottleneck in production and allow faster shipping time for the final product.

Hot air processing involves circulating hot air to raise the product temperature, followed by rapid lowering of pressure with vacuum pumps to evaporate water. Since heating must be completed before the vacuum step, the process takes more time.

Hot oil spray drying allows heating with a spray of hot transformer oil while pulling vacuum to remove water. This enables an overlap of heat and vacuum, which short-

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ens processing time. However, the combination of vacuum and heat can cause lighter fractions of the transformer oil to be removed with the vacuum. This alters its viscosity characteristics.

Vapor phase drying, like hot oil spray drying, uses a hydrocarbon to add heat concurrent with vacuum drying. The hydrocarbon selected has a boiling range that is narrow and relatively low so that it can all be removed from the drying process prior to introduction of transformer oil. Also, unlike the hot oil spray method, the cellulose does not become impregnated with the heating fluid nor transformer oil until drying is complete.

The vapor phase process provides the most efficient combination of heat addition and vacuum application. This results in the reduction of processing time by approximately 25 % over hot oil spray processing, and approximately 40 % over hot air processing. Time saved can amount to several days in processing time savings.

Benefits to thorough drying

Transformers will gain moisture once in operation through ingress from the outside and from breakdown of cellulose

in the presence of heat and energy. More than 99 % of that water will reside in the cellulose insulation with only a tiny fraction residing in the oil.

In addition, water and the oxygen in the cellulose provide a catalyst for degradation of the paper and the oil. Water in the oil and the paper lowers dielectric strength of both.

Therefore, it is desirable to start with an insulation system that is as dry as is reasonably possible.

Figure 2 shows the molecular structure of a cellulose molecule chain.

Challenges to efficient drying

Water can be efficiently removed by turning it from liquid to vapor (evaporation). Evaporation of water can be accomplished by raising the temperature, reducing the pressure or both.

A significant amount of heat, the latent heat of evaporation (970.3 btu/lb or 2,257 kJ/kg), is required to convert water from liquid to vapor at constant temperature. Heat also increases the diffusion rate in paper and increases the water vapor pressure so that it

Vapor phase drying is the most effective method for drying transformer insulation in a manufacturing setting



Figure 1. Cellulosic insulation

Water can be efficiently removed by turning it from liquid to vapor, which can be achieved by raising the temperature, reducing the pressure or both

can be extracted. The water vapor leaving the system takes this heat energy with it. Thus, it must be replaced to continue the process and to prevent the temperature of the coil from dropping during drying.

Lowering the pressure (pulling vacuum) reduces the temperature at which water will convert to vapor. The vacuum pumps also provide the transport mechanism for removal of the evolving water vapor. However, pulling vacuum does not negate the need to replace the latent heat of evaporation.

The diagram in Figure 3 shows the effect of temperature and pressure on the three main phases of water. Lowering the pressure – even at room temperature – from 'A' to 'B' allows water to evolve from liquid to vapor as long as enough heat is added to replace latent heat of evaporation and the temperature is not allowed to drop (to the left) into the ice (solid) phase region.

In the absence of air (vacuum), the options for replacing the lost latent heat are fewer since there is little air to circulate.

Heating the mass prior to pulling vacuum and relying on the residual heat in the coil has limitations as well. This technique doesn't allow for significant water removal during the heating phase which increases the processing time. Whether or not sufficient heat can be added ahead of vacuum application is highly dependent on the mass and material makeup of the load, the upper temperature limit (often <120 °C) allowable for the materials, and the moisture content. Without the addition of heat during the vacuum process, the insulation temperature will drop as water evaporates slowing the drying process to a possible stall.

Vapor phase principles & process evolution

The most efficient method of drying, therefore, is to simultaneously raise the temperature of the materials being dried while reducing the water vapor partial pressure by pulling vacuum.

In the vapor phase process, this is achieved by simultaneously reducing the pressure in the vapor phase chamber while circulating a hot fluid into the chamber as a heat transport medium.

The hot vapor is often referred to as 'kerosene' or 'solvent' although most processes use a narrower cut from kerosene stock that has a smaller range between its Initial Boiling Point (IBP) and its Final Boiling Point (FBP) such as Isopar K. This is discussed further below.

External vapor boilers: Early vapor phase systems often used external boilers to heat the solvent into a vapor that was then introduced into the chamber which was under vacuum. As the vapor came into contact with the load, it transferred its latent heat energy as it condensed from

vapor to liquid on the cooler surfaces of the load. The heat being removed by evaporating water was replaced in this manner.

In the absence of precise controls for pressure in the vapor phase, significant solvent vapor would leave the chamber with the water vapor producing a mixture of water and solvent that had to be condensed into liquid again and separated for collection. External boilers were problematic and overall energy efficiency was poor.

Liquid spray systems: Modern vapor phases are able to control the chamber pressure level as a function of temperature so that solvent can be heated and sprayed in liquid form (Figure 4), transferring sensible heat to the load, and largely remain in liquid form due to pressure control. This technique has the effect of minimizing carry-over of solvent into the vacuum stream and reduces condenser loads and the collection system volume. The control of both critical parameters of temperature and pressure provides more precise control over the drying process.

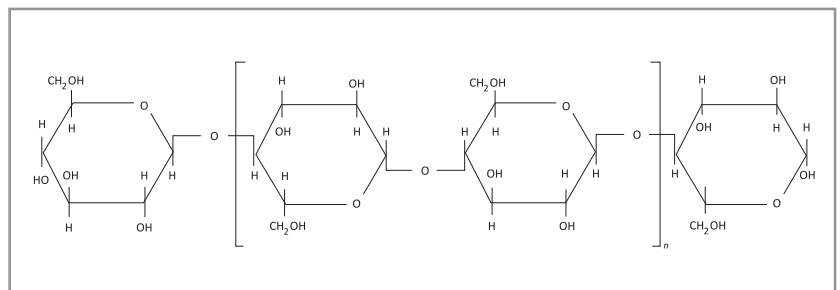


Figure 2. Cellulose molecule chain (C₆H₁₀O₅)_n

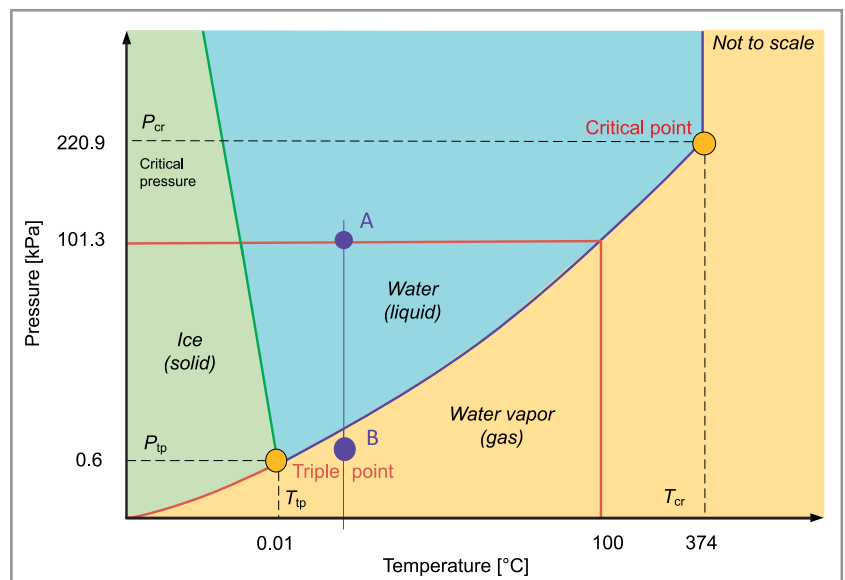


Figure 3. The effect of temperature and pressure on the three main phases of water



Figure 4. Modern vapor phase solvent spray

The vapor pressure curve for 'kerosene' lies approximately midway between that for water and oil, ensuring significant separation at all pressure and temperature combinations

To make up for the lack of latent heat transfer (formerly transferred through the old method of solvent vapor condensing into liquid on the load), higher liquid

mass flow rates are provided through the spray system. The rate of heat transfer to the load is as good as or better than the old method and no external boiler is required.

The overall system is more efficient because more of the solvent remains in the vapor phase chamber rather than exiting through the vacuum system requiring makeup.

Vapor phase fluid

The fluid to be used as a heat transfer medium must have a number of important characteristics:

- A narrow boiling point range to allow for precise control of temperature under vacuum; for example: Isopar K has an IBP of 360 °F and End Point of 395 °F (182 – 202 °C)
- Low aromatic content to minimize reaction with materials at processing temperature
- Good heat transfer qualities
- Ease of removal from the process chamber at the completion of drying
- Not detrimental to the dielectric breakdown voltage or flashpoint of the transformer oil used for impregnation

The chart in Figure 5 shows that the vapor pressure curve for 'kerosene' lies approxi-



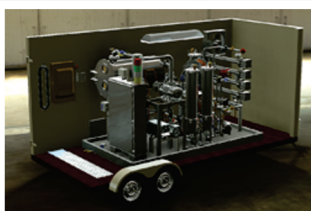
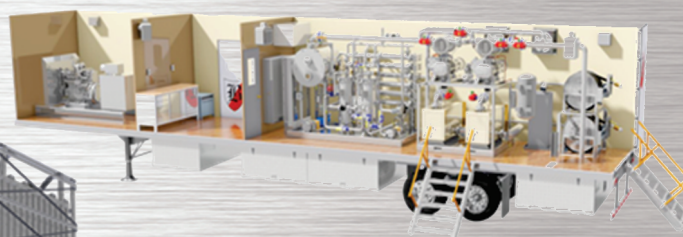
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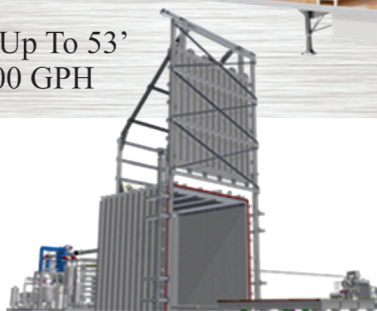
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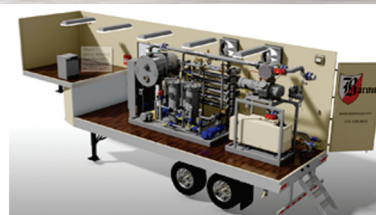
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Lowering the pressure, water can be evaporated, and by simultaneously controlling the pressure vs. temperature, the solvent can be kept largely in liquid form

mately midway between that for water and transformer oil and that there is significant separation at all pressure and temperature combinations.

It can be seen from Figure 5 that by lowering the pressure, water can be evaporated, and by simultaneously controlling the pressure vs. temperature, the solvent can be kept largely in liquid form so that it remains inside the chamber for recirculation, reheating and spraying in a continuous heating loop.

The pressure-temperature nomograph in Figure 6 shows just water and kerosene with their boiling points corrected for vacuum. The separation of boiling points can be seen on left line 'A' illustrating that the water will vaporize while the solvent remains liquid at the selected temperature and pressure.

At 20 Torr (26 mbar) vacuum, water will evaporate at >40 °F (4.4 °C), while Isopar K remains liquid below about 175 °F (79 °C). This means Isopar K can be sprayed on the load near this temperature, give up sensible heat to the load, and drop enough in temperature for it to remain liquid so as not to be carried out of the chamber by the vacuum stream.

Solvent temperature and vacuum levels can be ramped, or controlled to achieve a desired rate of temperature rise in the load or for the fastest rate of load temperature rise possible. PID (proportional-integral-derivative) controls can be tuned to adjust, as the load nears the upper temperature limit, to minimize temperature overshoot.

In the second part of this paper, typical vapor phase steps, vacuum chamber configurations, solvent handling and recovery, and other details of the drying process will be presented and discussed.

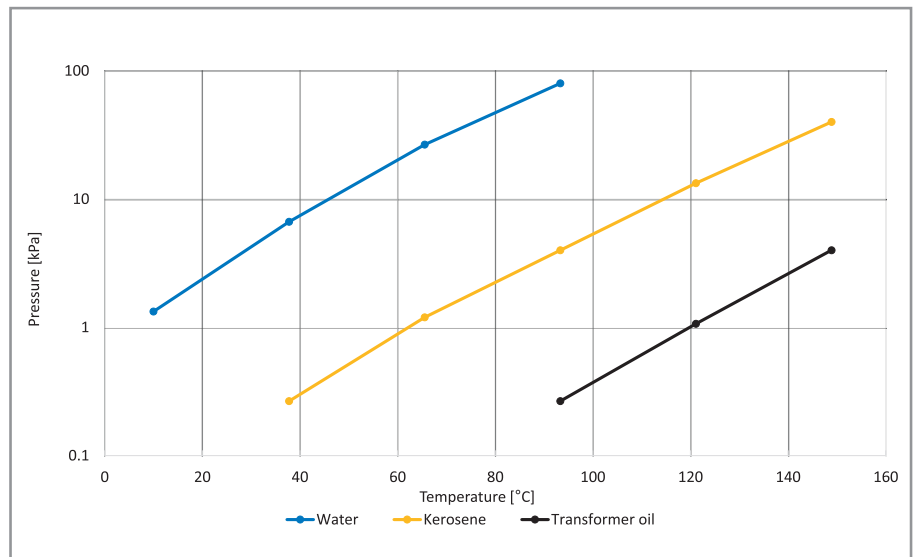


Figure 5. Water, solvent, and transformer oil vapor pressure curves

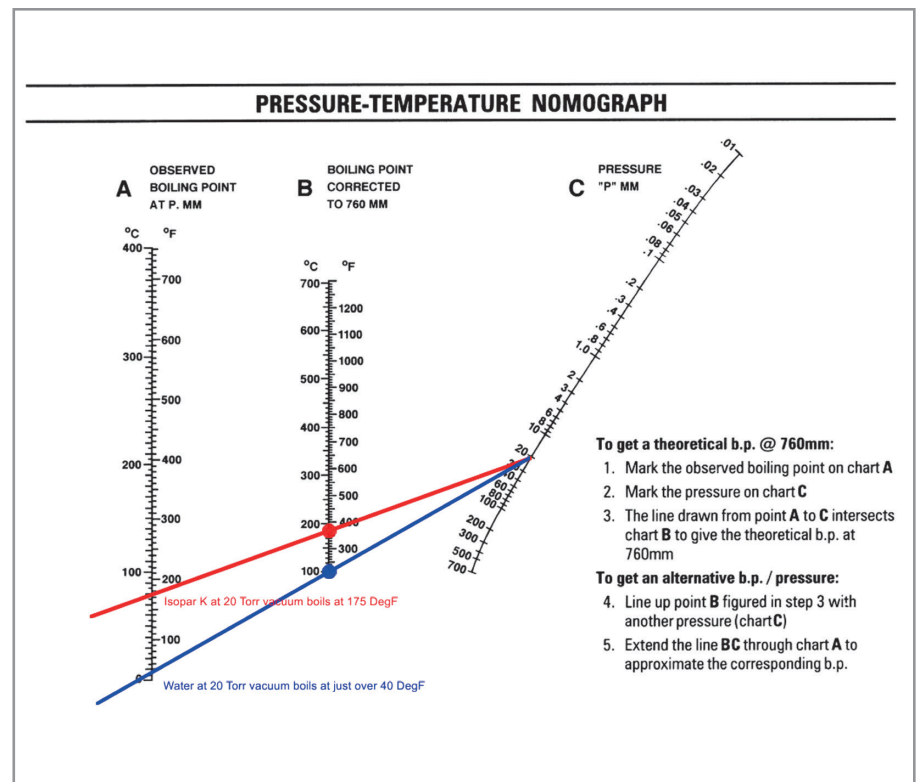


Figure 6. Kerosene and water boiling points corrected for vacuum on a nomograph

Author



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