2.8. Beyond 85/85: Towards Realistic Lifetime Estimation of Polypropylene Film Capacitors in Humid Environments

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ABSTRACT

Lifetime modeling in polypropylene film capacitors (PPFCs) is driven by the need to provide reliable estimations in a key component for numerous applications. Usually, accelerated tests are exploited to fit simplistic models. However, as discussed in the paper, in many cases they can give very approximate or even wrong results, especially in presence of humidity. Here, different degradation mechanisms in PFFCs are discussed, together with their impact on the lifetime component, and for which environmental conditions they are more likely to occur. Starting from these considerations, YAGEO KEMET developed a proper KEMET Lifetime Expectancy Model (K-LEM), strongly based on experimental results in realistic conditions. The use of this tool can help Customers and designers to choose the proper component and to have a realistic estimation of performance in their application.

INTRODUCTION

Polypropylene film capacitors (PPFCs) are widely used in power electronics, signal processing, and industrial applications due to their superior electrical properties, thermal stability, and long operational life. These capacitors are constructed using biaxially oriented polypropylene films as dielectric material, offering low dielectric loss, high insulation resistance, and excellent self-healing capabilities. Their performance under high voltage and temperature stress makes them especially suitable for demanding applications such as DC-link and AC filtering in power converters and EMI suppression in AC mains.

Key studies and standards have laid the groundwork for understanding and improving PP film capacitor technology. For instance, the comprehensive analysis of failure modes by Lothar and Krämer (2005) [1], and the extensive review of dielectric materials for film capacitors by Xu (2004) [2], provide foundational insights into their development. Additionally, IEC standards such as IEC 60384-16 [3] define performance requirements and testing methodologies critical to ensuring capacitor reliability.

Traditional lifetime estimation models often overlook the significant impact of humidity, leading to inaccurate predictions and potentially unexpected failures. While manufacturers frequently categorize capacitors based on "grade" or "endurance" ratings, Customers often fall into the trap of assuming a direct correlation between higher grade and universally extended lifetime, irrespective of environmental conditions. This simplification ignores the complex interplay between temperature, humidity, and the inherent material properties of PPFCs, ultimately hindering accurate lifespan projections.

In this paper, main degradation mechanisms in PFFCs are presented, showing how they are triggered by environmental conditions, and in particular by humidity. Starting from these observations, the YAGEO KEMET Lifetime Expectancy Model (K-LEM) is presented and discussed, explaining how it uses long term tests in realistic condition to compute lifetime estimations with a high degree of confidence level.

FAILURE MECHANISMS IN HUMID ENVIRONMENT

The introduction of humidity into lifetime estimation models is paramount due to its profound influence on PPFC degradation. Moisture ingress, driven by vapor pressure gradients and material permeability, triggers a cascade of failure mechanisms, especially at high temperatures. Even at lower temperatures but still high RH, condensation can occur, creating localized water films that facilitate ionic migration and accelerate corrosion of the metallized film.

Furthermore, a deeper understanding of failure mechanisms, particularly in the presence of humidity, is crucial. In Fig. 1a) different Temperature-Relative Humidity regions are schematically defined diving the domain in different absolute humidity levels:

1) for absolute humidity < 15 g/m^3 (in light blue) dry condition can be considered. It means that humidity effect is not so meaningful on component
2) for absolute humidity between 15 and 20 g/m^3 (in green), moisture starts to impact on device lifetime. This environmental condition can be easily found in several realistic applications and in many geographical regions.
3) for absolute humidity between 20 and 30 g/m^3 (in orange), harsh humid environmental condition must be considered, since moisture can affect in a relevant way the capacitor lifetime. This condition can be found in some realistic application, especially if located in geographical regions with a high degree of humidity.
4) for absolute humidity between 30 and 60 (in dark orange), very harsh humid condition occurs. This can occasionally happen in realistic conditions, for instance in case of sealed environment, such as IP55 and so on applications. Also, some THB accelerated tests (i.e. 40 °C 93% RH) lie on this region.
5) for absolute humidity above 60 g/m^3 (in red), only accelerated test conditions can be considered. Indeed, such high values cannot happen in any realistic application, and they are obtained only in closed chamber laboratory tests.

In Fig. 1a) it is also schematically shown which are the main degradation mechanisms in PFFCs acting for different temperature/relative humidity conditions. Finally, as reference to realistic environmental conditions, in Fig. 1b) average absolute humidity for different geographical areas is depicted. It can be observed that the maximum value is around 30 g/m^3, occurring only in few areas.

First of all, partial discharges (PDs) are a significant concern in PPFCs subject to AC voltage, especially under humid conditions. KEMET advanced testing capabilities allow for detailed characterization of PD behavior under various temperature and humidity conditions, providing valuable insights into the initiation and propagation of PD-related failures. By analyzing PD patterns and correlating them with environmental parameters, KEMET can develop more accurate models for predicting PD-induced degradation and improving capacitor design.

Instead, electrochemical corrosion occurs when conductive paths form due to the presence of moisture and an electric field, leading to localized degradation of the metal electrodes. This phenomenon is especially pronounced under high relative humidity (>75%) and elevated temperatures (typically 60–85 °C), where ionic conduction through the polymer film becomes significant.

Conversely, oxidation of the metallized electrodes—commonly composed of zinc or aluminum—results from exposure to oxygen and heat, It occurs also in the absence of an external current, even if DC voltage can trigger and increase its effect. Oxidation reduces the effective electrode conductivity and impairs the capacitor's self-healing capability. This effect becomes critical at temperatures above 85 °C and is accelerated by the presence of residual moisture or permeation through imperfect sealing. Together, these mechanisms can lead to increased equivalent series resistance (ESR), capacitance drift, and eventual failure.

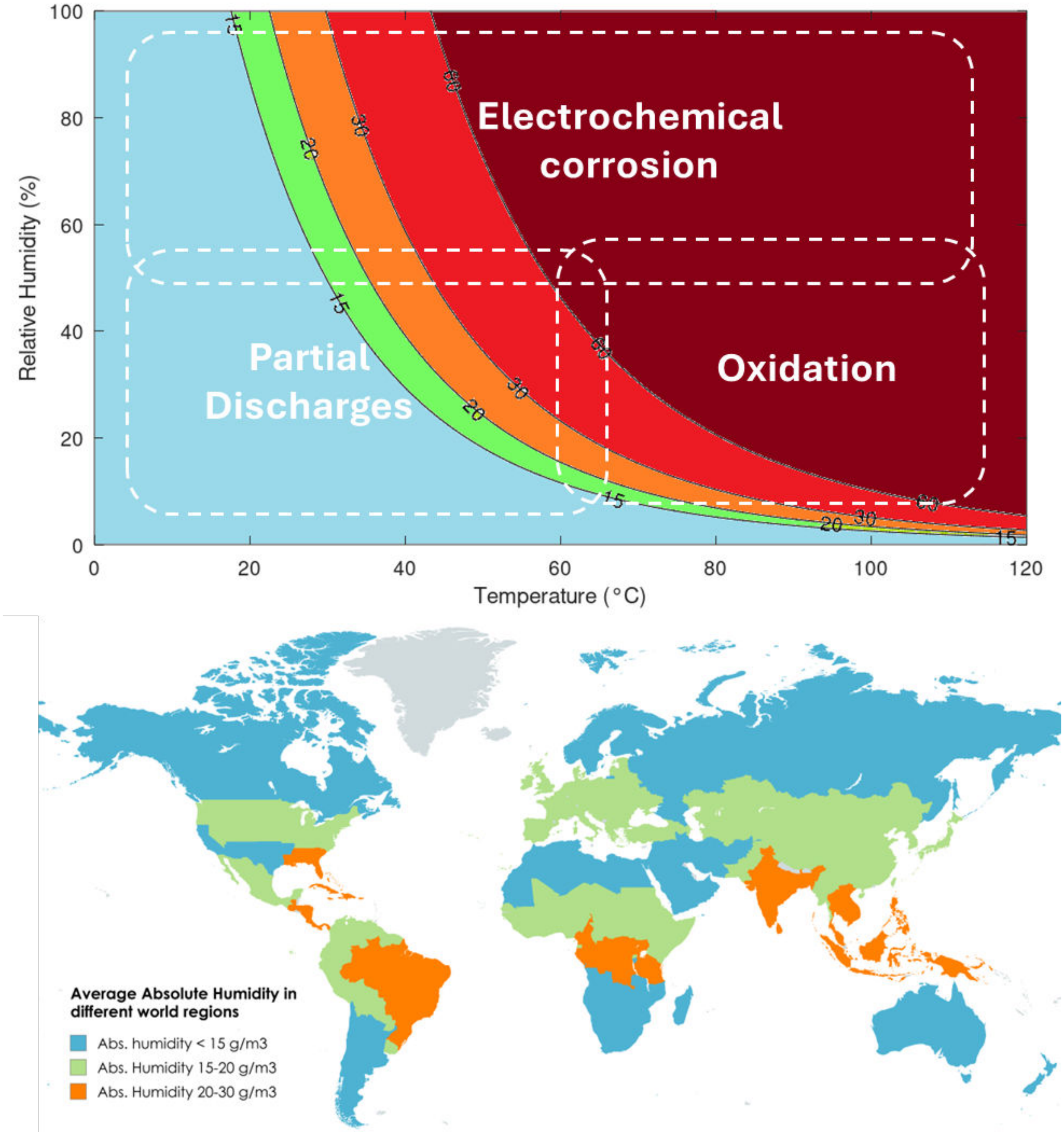

Fig. 1. Upper panel: Temperature-Relative Humidity domain vs Absolute Humidity levels with main degradation mechanisms acting in different environmental conditions. Lower panel: Average Absolute Humidity distribution in different world regions.

PROPER TESTING METHODS FOR REALISTIC ENVIRONMENTAL CONDITIONS

A significant challenge in developing accurate humidity-dependent lifetime models lies in the difficulty of obtaining comprehensive environmental data from real-world applications. This data scarcity reinforces the reliance on simplistic grade-based lifetime estimations, which are often insufficient for predicting performance in diverse and demanding environments.

Traditional accelerated testing methods, such as Temperature-Humidity-Bias (THB) tests (e.g., 85°C/85%RH), have been instrumental in assessing capacitor reliability. However, these tests often subject capacitors to extreme conditions that deviate significantly from real-world operational scenarios. While they offer valuable insights into intrinsic material weaknesses, they fail to capture the less aggressive degradation mechanisms that occur under realistic temperature and humidity conditions. The "race" to achieve ever-higher endurance ratings at extreme

THB conditions (e.g., 1000 hours, 2000 hours, or beyond) at 85°C/85%RH, while seemingly impressive, can mislead Customers by neglecting the importance of realistic environmental profiles.

Indeed, as already shown in Fig. 1b), in all main geographical regions the maximum absolute humidity is below 30 g/m^3, far away from 300 g/m^3 of 85°C/85%RH test. In the latter condition, degradation is mainly driven by strong and accelerated electrochemical corrosion, while in realistic conditions, as explained above, partial discharges and oxidation play the most important role.

Then, to better predict lifetime and improve know-how, a strong focus on proper testing is necessary. This includes developing and implementing advanced testing methodologies that go beyond standard THB tests. Endurance tests at different environmental conditions, impedance spectroscopy, combined with advanced film characterization techniques such as scanning electron microscopy (SEM), inductively coupled plasma spectroscopy (ICP), or X-ray photoelectron spectroscopy (XPS) can provide a comprehensive understanding of the degradation mechanisms occurring under real-world conditions. Additionally, in-situ monitoring of key parameters, such as capacitance, dissipation factor, and leakage current, during environmental voltage testing can provide valuable insights into the progression of degradation.

YAGEO KEMET LIFETIME EXPECTANCY MODEL (K-LEM)

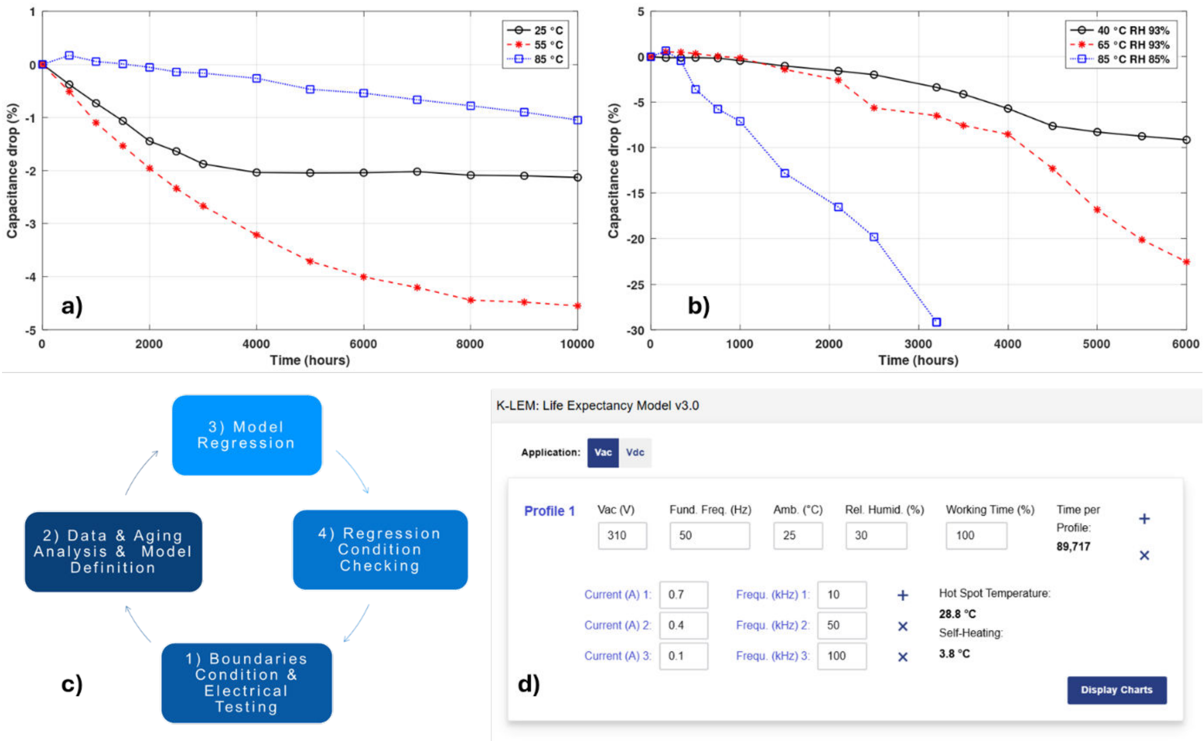

Fig. 2 a) Example of AC voltage long-term tests used for K-LEM model definition in dry conditions at 25 °C (black solid line), 55 °C (red dashed line), and 85 °C (blue dotted line), respectively with its results. b) Example of long-term tests used for K-LEM model definition in harsh environment at 40 °C 93% RH (black solid line), 65 °C 93% RH (red dashed line), and 85 °C 85% RH (blue dotted line), respectively with its results. c) Schematical logic loop for K-LEM development. Starting from electrical testing, data are analyzed, and the model is defined. Then, a proper non-linear regression is performed. Finally, regression results are checked in loop with measurements. d) Snapshot of K-LEM web interface, where the customer can input boundary conditions and, if present, harmonic load components. The interface allows to combine up to 5 different conditions with each working time percentage, to meet more complex mission profiles.

In this view, YAGEO KEMET provided both theoretical and experimental studies [4-7], to shed light on physical mechanisms in film capacitors. Moreover, to provide reliable lifetime prediction, KEMET YAGEO developed the KEMET Lifetime Expectancy Model (K-LEM) [8]. It is a powerful tool that can help circuit designers predict the service life of metallized film capacitors that can withstand harsh environmental conditions. It has been the first tool of its kind to consider three key factors in a Film Capacitor's life: Ambient Temperature, Relative Humidity, and Applied Voltage Bias, with the possibility to apply also current harmonic load. It is a proprietary model strongly based on long term experimental measurements in numerous environmental conditions. In addition to standard THB tests, K-LEM includes realistic conditions for the most significant applications, such as solar and wind plants, power supplies for domestic systems and data centers, charging stations/on board chargers for automotive. In all the previous cases, the absolute humidity is below 30 g/m^3, with relative humidity varying from 20 to 90%, according to the geographical area. Conversely, 85 °C/85% RH THB test implies 300 g/m^3, ten times more the harshest realistic condition. In this view, K-LEM gives more weight to probable environmental conditions thank to KEMET extended experimental database. Such data are then exploited to develop the mathematical prediction model, with the aim to achieve a confidence level up to 95% in the realistic temperature/humidity domain.

As an example, in Fig 2a-b some of the long-term AC voltage tests used for K-LEM model in a grade IIIB suppressor (R53 KEMET series) are reported with its results. In Fig 2a) capacitance degradation vs time in dry conditions (Absolute Humidity < 15 g/m^3) at 25, 55 and 85 °C are shown, respectively. It can be noted the intrinsic different behavior with temperature. Indeed, at low temperatures, where PDs are somehow relevant, an initial higher capacitance drop is observed, with a successive stabilization. This behavior can be explained with some physical considerations. The operating voltage is constant during the test, and then also the average available energy in PDs. At the beginning of the test, such energy is more likely to remove the metallized region near to the free margin -with a lower metal quantity -, causing a fast capacitance drop. After this first phase, the actual metal edge involved by PDs to possible degradation has an higher metal quantity which is hardly or partially removed by the available PD energy. The consequence is that the capacitance drop shows a much lower slope (near to a plateau) after certain time, as visible in the 25 °C and 55 °C curves. Instead, at 85 °C it starts to be more meaningful the oxidation phenomena. In the latter case, a quite constant capacitance drop during time is observed, having a lower average slope with respect to the initial portion of 25 °C and 55 °C curves. Of course, the trends shown in Fig 2a) are only for illustrative purposes, since the general behavior that can be different, according to the series, the capacitance and the considered applied conditions.

As visible in Fig. 2b), the capacitance drop behavior in case of THB accelerated tests is profoundly different. All tests are performed at rated voltage (310 Vac for this series). In all these cases the main degradation mechanism is electrochemical corrosion that leads to a very rapid capacitance decrease, somehow proportional to the absolute humidity of the test. Indeed, the drop is increasing by observing 40 °C 93% RH (50 g/m^3), 65 °C 93% RH (150 g/m^3) and 85 °C 85% RH (300 g/m^3) curves. Moreover, no plateau or regions with decreased slope are observed. This is a clear indication that exploiting only accelerated THB tests for forecasting capacitor performance in realistic applications may lead to very approximate or even wrong results.

Starting from these considerations, KEMET developed K-LEM model. In Fig. 2c) the K-LEM schematic logic loop is shown. The modeling strategy is based on a strong electrical testing, exploiting up to 18 different conditions that can cover the whole T-RH domain avoiding the misuse of THB tests. Then, after data analysis and model definition, a proper non-linear regression is performed. Finally, the model is verified in loop with additional data to tune and optimize it. In Fig. 2d) the web online interface is shown. Customer can choose the series with the PN in a proper cascade menu. Then, boundary conditions can be inserted, together with harmonic components if present. After that. the interface gives back the corresponding lifetime estimation. The interface allows to combine up to 5 different conditions to be compliant to more complex mission profiles.

As an example of the abovementioned statements, R53 series (grade IIIB suppressor) has a 85°C 85% RH lifetime exceeding 1000 hours, while its grade IIB counterpart (R52 series) reaches results above 500 hours. In this case, the lifetime increase of R53 with respect to R52 is around 100%. Conversely, evaluating the same series in realistic conditions, the increase can be between 20% and 50%. Also in this case, component dimensions, capacitance range, and applied conditions can lead to different relative results.

SUMMARY AND CONCLUSION

In conclusion, accurate lifetime estimation of PPFCs in humid environments requires a paradigm shift from simplistic grade-based assumptions and reliance on extreme THB tests. By incorporating realistic environmental data, focusing on the specific failure mechanisms triggered by humidity, and leveraging advanced testing capabilities, K-LEM can move towards more reliable and predictive models that accurately reflect the performance of PPFCs in real-world applications. This will enable customers to make informed decisions about capacitor selection and ensure the long-term reliability of their electronic systems at a fair price.

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