THERMAL ANALYSIS AND PROFILE OF FILM CAPACITORS FOR HIGH CURRENT APPLICATIONS

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ABSTRACT

Film capacitors have been used in high current applications ranging from 1 ampere to 60 amps for sometime. Applications such as SwitchMode Power Supplies, and high frequency welders stress the capacitor in operation. To avoid premature failure, attention must be paid to the thermal characteristics of the capacitor system. In many applications, the thermal effects of the ambient environment are overshadowed by the capacitor's own self generated heat. Often this heat creates degenerative effects.

Heat in capacitors can be developed by several sources, namely the dielectric, the electrode system, the end termination system, the leads, all combined in the ESR of the capacitor, and of course the operating current level. The selection of materials used in the capacitor construction has a direct relationship to the thermal effects. The thermal conductivity of the various materials can be managed to some extent to allow for better cooling.

The major conduction paths are the axial and radial modes. Examination of the thermal conductivity of the construction materials with regard to the appropriate mode gives clues as to major paths for heat removal. Convective cooling models for natural and forced air systems and general equations give application information.

Experimental data gives empirical proof of the models and also examines the shortcomings of general rules. Very high current applications are profiled and the data can be examined.

Finally, design physical aspects, and alternate materials selections may be explored and the effects on the thermal system examined to provide leeway for the user.

INTRODUCTION

Film capacitors have been used in high current applications for a long time. Currents from 1 to 60 amperes RMS are common. Applications such as switchmode power supplies and high frequency welders place the film capacitor under considerable stress. Why is it that some capacitors seem to function well while others die in a wisp of smoke and a mass of black goo? Attention must be paid to the thermal characteristics of the capacitor system if such problems are to be avoided. Often, the capacitor's own self generated heat overshadows the surrounding environment. Such a condition can cause degenerative effects. This paper will examine the sources of heat, and the methods to keep the temperature rise under control.

SOURCES OF HEAT

The capacitor system has several features that contribute to the generation of heat or the removal of heat generated. These are the dielectric material, the electrodes of the capacitor, the termination between the electrodes and the leads, and the leads themselves. Each element plays an important part.

The dielectric materials to be used in the capacitors are selected on several characteristics. The operating temperature capability, dielectric strength at elevated temperatures, material cost, dielectric constant and dissipation factor characteristics are of prime importance. Of these, the temperature capability and dissipation factor are primary. The dissipation factor characteristics of several popular dielectrics are shown in figures 1 & 2. Note that variations with temperature and frequency are shown. Popular dielectric choices include Polypropylene, Polycarbonate and Polyester. The new dielectric Polyphenylene Sulfide (PPS) holds promise as another good choice. When evaluating the dielectric system one should examine the dissipation factor curves at the frequency of concern and the final internal temperature of the capacitor when operated at rated current. The internal temperature is the external ambient temperature plus the thermal rise within the capacitor.

DISSIPATION FACTOR VS. TEMPERATURE

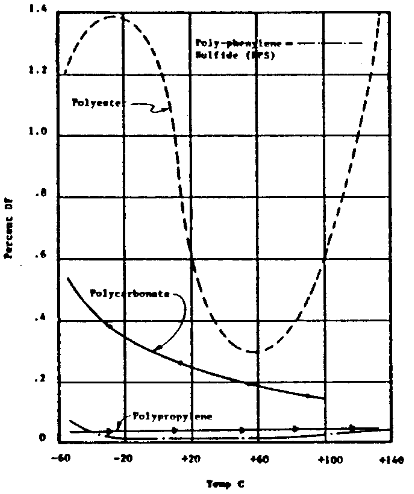


FIG. 1

DISSIPATION FACTOR VS. FREQUENCY

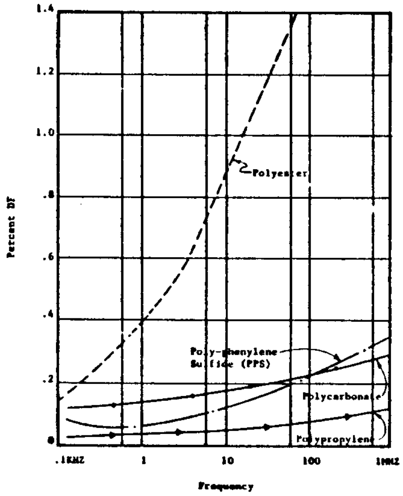


FIG. 2

The second consideration for heat generation/removal is the electrode system. Typical film capacitor systems are shown in Figure 3. Shown are film foil and metallized constructions. Each construction has its advantages. Film foil construction has good current handling capability, high thermal conductivity, but gives larger sizes. Metallized construction will self heal and offers reduced sizes, but has poorer heat conductivity and is current limited. The current passing through the electrode system produces I^2R losses. For a film-foil capacitor this is of little consequence. However, in a metallized capacitor the electrode resistivity can range from .5 ohm/square to 10 ohms/square. These varying resistivities are utilized depending upon the intended application. Many 60 hz AC rated capacitors use the higher resistivities to achieve good life performance but are not suited for high current applications since the high resistivities cause significant self heating and poor thermal conductivity.

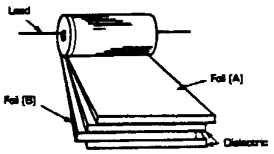
The third consideration is the termination of the electrode. Film-foil capacitors can be soldered or schooped (metal sprayed). Metallized capacitors must be schooped. The schooped film-foil offers the highest current capacity and the best thermal conductivity. The metallized capacitor is somewhat sensitive to the selection of schooping spray material and the process used to apply it. Optimal performance must consider these factors.

The fourth consideration is the connecting leads. Typical choices are oxygen free copper or Tinned copper weld (TCW) wire. TCW is a tinned, copper sheathed, steel cored wire, also known as copper covered steel (CCS). Multiple leads, stranded wire leads, copper tabs and threaded studs are additional choices. The key point is that the termination process and the leads selected should not cause degenerating damage to the end of the capacitor. Figure 4 gives details of these leads.

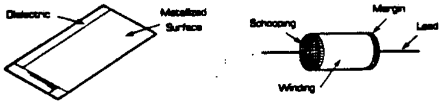
HEAT-GENERATION

The heat from the capacitor is generated by the current flowing. While the current waveform is not always sinusoidal, the RMS value must be considered when calculating the heat generated. Non sinusoid waveforms with high peak currents may stress the termination and cause localized heating.

WOUND CAPACITOR



Two Foils - Two Dielectric - Thicknesses
Margins
Start & End Margins
Foil Extensions



Size Reduction - Eliminate Foil
Schooping - Termination Interface
Clearing - Fault Removal
Reliability

FIG. 3

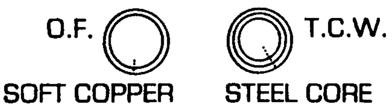
However, such conditions must be considered separately. The power dissipated in the capacitor can be calculated from one of the following formulas.

DESIGN CONSIDERATION

LEADS

- of solid copper
- multi-lead & tab

TIN COATING



SOFT COPPER	STEEL CORE
Soft	Stiff
Wire Wrap	Auto Insertion
Non-Magnetic	Reel Pack
	Conductivity - 30%

FIG. 4

$P=2pFCV^2DF$ (EQ 1)

$P=I\ DF/2pFC$ (EQ 2)

$P=I^2ESR$ (EQ 3)

Where: P = Power dissipated in Watts
F = Frequency of waveform
C = Capacitance in Farads
V = RMS voltage of waveform
DF = Dissipation factor of capacitor at frequency F
I = RMS current
ESR = Equivalent Series Resistance in ohms

SIZE AND SHAPE EFFECTS ON CURRENT HANDLING

The size and shape of the capacitor has a direct relationship to its ability to handle current. It also has an effect upon the thermal characteristics.

The size of a capacitor is directly related to its capacitance and voltage rating. The voltage stress upon the capacitor dielectric dictates what thickness of dielectric is employed. Reliability considerations may require an increase in dielectric thickness so that voltage derating can be utilized. Obviously, the capacitance value dictates how large the capacitor is for the dielectric thickness selected. Within the restrictions imposed by these basic considerations, much flexibility remains. The width of the dielectric material can be varied to create a variety of aspect ratios. That is, the capacitor's diameter or thickness/width versus length. Improved material consumption efficiency leads one towards greater material widths and thus longer body lengths.

However, when considering current handling and inductance, one must think in regard to current path lengths. The current flowing through the capacitor enters the capacitor lead, flows through the termination, through the electrode, couples through the dielectric by the electric field, and out through the other electrode, termination, and lead. Since the leads are external the user controls the length. Within the capacitor, the current path is controlled by the electrode width. The current flowing through the termination spreads along the entire length of the wound layer through the schooping. Thus, the electrode width defines the current path length. Figure 3 helps illustrate this point. A natural conclusion is that since there are two electrodes, the path length is twice the electrode width. This is untrue since the capacitance is distributed across the width; therefore, only one width is considered.

As will be seen later, heat removal is via two modes, surface convection and core conduction. Both relate to size and shape.

As a general rule, the shorter the current path, the lower the inductance of the capacitor and electrode heating from I^2R losses. The bottom line is: SHORT AND FAT IS THE BEST, LONG AND THIN IS THE WORST.

HEAT REMOVAL FROM A CAPACITOR

In normal applications the primary method for cooling the capacitor is through convection. Some exotic designs for high power utilize conductive systems such as heat pipes or water cooling systems. While highly effective for large welders, etc., normal applications such as switchmode power supplies preclude their use.

HEAT REMOVAL — THERMO PROBLEM

SURFACE REMOVAL — CONVECTIVE COOLING

$$\Delta T_{SKIN} - \text{Fluid} = \frac{Q}{H\ A_{(SURFACE)}}$$

$$\Delta T = 176\ \frac{P_{(WATTS)}}{A_{(IN^2)}}$$

Forced air improves removal 3 to 10 times

$$\Delta T = 35\ \frac{P}{A}$$

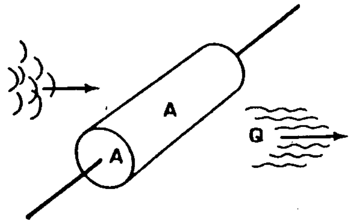


FIG. 5

Figure 5 illustrates a typical convective cooling model. From thermodynamics we understand that in order to get heat flow, we must have a temperature differential. In this figure, there exists a temperature differential between the skin of the capacitor and the fluid (air) in which it is immersed. In the figure, delta T is the temperature differential of the skin and the fluid. Q represents the heat flow. H is the convective heat transfer coefficient. A is the surface area immersed in the fluid. This equation can be reduced to the form:

$$\text{Delta } T = 176\ (P/A) \qquad \text{(EQ 4)}$$

Where:

ΔT = temperature difference of the skin and the fluid
P = the power dissipated in watts from equation 1,2, or 3
A = the surface area of the capacitor in square inches.

The constant 176 is developed empirically and represents still ambient air.

Forced air convection (i.e. approx 200cfm) causes an improvement in the cooling by 3 to 10 times. For such cases, the 176 constant changes to approximately 35. It should be noted that different test setups result in varying constants. Mil-Std-198 has an application curve that equates to about 125. While such variations seem large, one should realize that many factors effect the heat flow, so that calculation only gets one in the ball park. Immersion in a fluid other than air would result in different coefficients. Also, lower density fluids (such as high altitude operation) can affect the coefficient.

CORE HEAT REMOVAL

Now that we have seen how to remove heat from the capacitor skin, we also must address the problem of removing heat from the core and body of the capacitor and getting it to the skin for convective cooling. Figure 6 illustrates the fact that the heat flow can be broken down into a axial and radial component. Again, a temperature differential must be present to have heat flow. Thus, the core is hotter than the skin and the skin is hotter than the fluid. If these conditions are not true, then the capacitor could become a heat sink for the air!

CORE HEAT REMOVAL — CONDUCTIVE COOLING

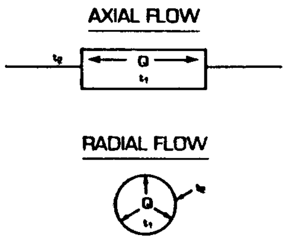
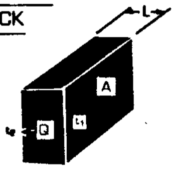


FIG. 6

To better understand the conduction through the capacitor interior, let's examine Figure 7.

CONDUCTION FORMULA FOR FLOW THROUGH BLOCK

$$\Delta T = \frac{Q\ L}{K\ A}$$



Typical K

Aluminum = .5
Polypropylene = 2.8 x 10^{-4}
Epoxy = 4.0 x 10^{-4}

T5871-110

FIG. 7

The formula for the conduction through a block is:

$$\Delta T = QL/KA \qquad \text{(EQ 5)}$$

The flow from t_1 to t_2 is through an area A along a path length L. The heat flowing is Q. The constant K represents the thermal conductivity and depends upon the material. Typical values for K are:

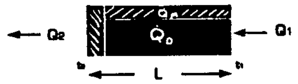
Aluminum = .5
Polypropylene = 2.8 x 10^{-4}
Epoxy = 4.0 x 10^{-4}

NOTE: Epoxies loaded with insulating, thermally conductive filler compounds such as alumina may have substantially improved thermal properties.

The above values of K tell an important story. Metals have 4 orders of magnitude more capability to conduct heat than do plastics. Within the plastics, the difference may be 2 or 3 times but all are in the same order of magnitude. We will see later what this large difference means.

Examine Figure 8. This figure depicts the axial flow through the electrode and dielectric. The diagram represents 1/2 of a typical metallized capacitor layer. Here we view the left half. The right half is identical, and we can assume that 1/2 of the axial heat flow component also flows to the right. We also can assume that the heat entering the layer Q_1 is the same as the heat leaving Q_2.

AXIAL FLOW THROUGH ELECTRODE & DIELECTRIC



$Q_1 = Q_M + Q_D = Q_2$

Comparison: 6.5 MFD

L	Electrode	QM	QD	QT	
375	Metallized Alum	.047	.003	.05	x ΔT
1.0	Metallized Alum	.0052	.0003	.0055	x ΔT
1.0	Aluminum Foil	.595	.00046	.595	x ΔT

FIG. 8

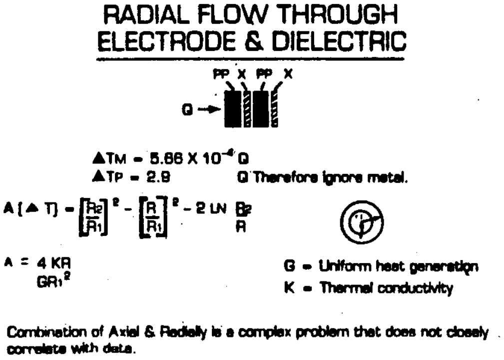
Also, we can assume that the heat flowing through the electrode Q_m and the heat flowing through the dielectric Q_d equals Q_1. Comparing three 6.5 MFD 32 gauge polypropylene designs gives some interesting information. The first design is a metallized design with a short path length of 3/8 inch (3/4 material width). The second design is also metallized with a 1 inch path length (2 inch material). Design three is an aluminum foil and film capacitor with a similar 1 inch path length.

Equation 5 can be rearranged.

$$Q = \Delta T(KA/L) \qquad \text{(EQ 6)}$$

The appropriate values for K, A, and L are substituted, and the result is given in the table. To get the heat flow Q, multiply the value in the table by the ΔT. Note that for the metallized designs, the heat flowing through the metallized layer is 10 times higher than through the dielectric. For the foil film design, the heat flowing through the metal is over 1000 higher! Also note that for the shorter path length the heat flowing is 15 times greater than for the longer path! This is the basis for the statement that short and fat designs are best. Of course the alum foil design is 10 times better than the metallized for the same path length. These numbers are revealing. Even though the metallized layer is a few hundred angstoms thick and the dielectric is .32 mils thick, the metallized layer conducts substantially more heat. Thus the thermal conductivities noted before are significant. This demonstrates another reason to avoid capacitors made with the higher resistivities.

RADIAL FLOW THROUGH
ELECTRODE & DIELECTRIC



$\Delta T_M = 5.66 \times 10^{-4}\,Q$

$\Delta T_P = 2.9\,Q$ Therefore ignore metal.

$$A(\Delta T) = \left[\frac{R_2}{R_1}\right]^2 - \left[\frac{R}{R_1}\right]^2 - 2\,\mathrm{LN}\,\frac{R_2}{R}$$

$$A = \frac{4KR}{GR_1^2}$$

G = Uniform heat generation
K = Thermal conductivity

Combination of Axial & Radially is a complex problem that does not closely correlate with data.

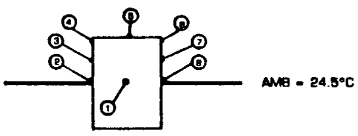
FIG. 9

Figure 9 describes the radial heat flow through the electrode and dielectric. In this mode the heat flow is through successive layers of plastic dielectric and metallized electrode. Again applying equation 5, we see that the temperature differential across the thin metal layer is 4 orders of magnitude less than across the plastic dielectric. Therefore in this mode we can ignore the metal layer. We could solve for the heat flow in the radial mode. However it suffices to say that the solution to the combination of axial and radial flow is complex considering all the variables present. It is beneficial to examine several experimental cases.

EXPERIMENTAL RESULTS

Figure 10 depicts a short, fat, metallized 6.5 mfd film capacitor instrumented with thermocouples and connected to a resonant tank circuit excited to give the currents noted. The ambient air was at 24.5 degrees C.

TEMPERATURE PROFILE TEST
AT 45 & 67 AMP RMS 40kHz UNCASED



T.C.	1	2	3	4	5	6	7	8
Temp°C 45 ARMS	53.5	48	47.5	49	43	56	53.5	50
67 ARMS	79	67	65	70.5	60	65.5	60.5	74

FIG. 10

Thermocouple #1 is located at the core of the capacitor. #2 is located at the lead egress from the endfill. The balance are located as shown. From the data table we deduce some interesting facts. The temperature differential from the core to the left side is about 6 degrees. The differential from the core to the top outside is about 10 degrees. This indicates lower thermal impedance towards the ends. However, the radial component is also contributing. The important point is that the skin temperature rise is fairly uniform. Note that the right side data is higher than the left side. This was a test anomaly due to radiation heating from the coil core which was on the right side of the capacitor. Reversing the capacitor location resulted in the right side again being hotter. Thus the left side data was considered to be the more accurate data.

FORCED AIR COOLING TEST

		ΔT Skin	ΔT Core
45 AMPRMS	Uncased	23°C	27°C
	Still-Cased	16°C	20°C
	Forced-Cased	2°C	5°C

FIG.11

Figure 11 shows the results of a forced air cooling test. The air source was a small 200CFM muffin fan. The data shows the effects of the capacitor's wrap and fill encasement. The delta T's shown were from the ambient to the skin and the ambient to the core. The uncased numbers show that the differential from the skin to the core is about 4 degrees. By wrap and fill encasement, the same part shows 7 degree cooler operation. This is due to the larger surface area. When forced air cooling is added, the skin rise drops to 2 degrees, and the core to skin differential drops to 3 degrees, demonstrating the improved heat removal. Note that the forced air demonstrated an 8 times improvement over the still air.

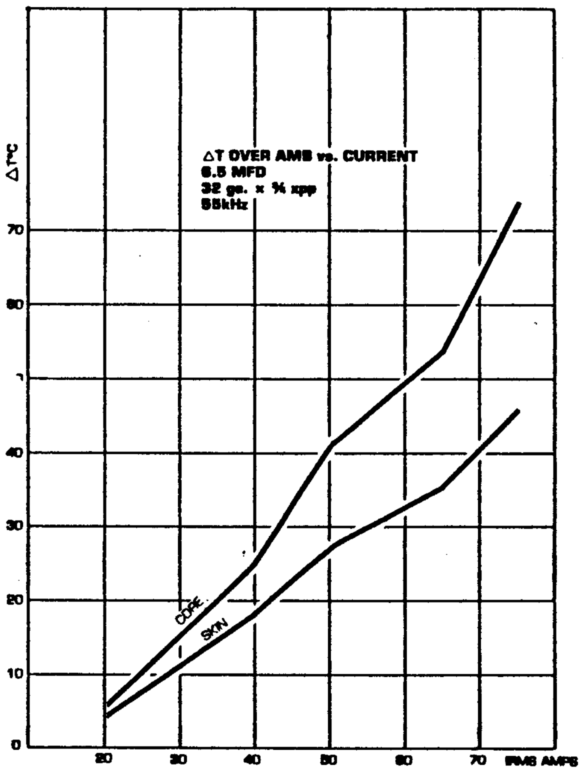


FIG.12

Figure 12 is an interesting graph. The capacitor is another short, fat design. The plot depicts the temperature rise over ambient still air for the skin and core at various RMS currents. We can see from this data that the temperature differential increases as the heat load increases. This is logical since the thermal properties of the capacitor are more or less fixed by the design and materials.

APPLYING THE LESSONS TO APPLICATIONS

So what does this all mean? From this information we can determine several operation rules.

First, the operating temperature limits for the capacitor must be observed. This means that the limit is applied to the core since that is where the heat is generated. The ambient operating temperature limit must be adjusted by the core to skin and skin to ambient drop. Thus, the application under high power conditions must be carefully studied and planned if reliable operation is to be achieved. Remember, the reliability equations state that failure rate doubles for every 10 degrees C change in temperature.

Second, size reduction of the capacitor will increase the skin temperature for a given set of operating conditions since the surface area is less. This will effect reliability.

Third, the use of forced air cooling can greatly improve the capability of the capacitor to withstand increased heat loads.

Fourth, the practice of packaging the capacitor last and thus needing odd form factors may have detrimental effects on the performance. It is suggested that the capacitor be dealt with early in the design cycle.

Finally, use the resources of your capacitor source to discuss these subjects. If they don't know what you are talking about, think twice about that source.

BIOGRAPHY

Ted von Kampen graduated with a B.S.E.E. from the University of Nebraska in 1964. He was then employed by the Rocketdyne Division of North American Aviation as an instrumentation Engineer. He joined TRW Capacitor Division in 1966. He has served as an application engineer, New products manager and engineering manager. He has authored several papers and has been active in AC capacitor development. He has specialized in high frequency power metallized polypropylene film capcitors.

Mr. von Kampen currently is employed by American ShiZuki Corporation (successor to TRW Capacitor Division) as Manager of Research and Development.