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EFFECT OF FILAMENT POWER REMOVAL ON A FLUORESCENT LAMP SYSTEM

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Abstract

Two techniques are used to measure the effect of removing the filament power from a two-lamp, F-40, rapid-start fluorescent lamp system. The changes are measured for a standard CBM core-coil ballast and for a solid-state ballast operating the lamp at high frequency. There is a 4 to 6% increase in system efficacy when the filament power is removed. Removal of filament power also decreases filament temperature from 1000°C to below 700°C in lamps operated at 60 Hz, and from above 600°C to 300°C in lamps operated at high frequency. The study shows that the arc current and anode fall also determine filament temperature.

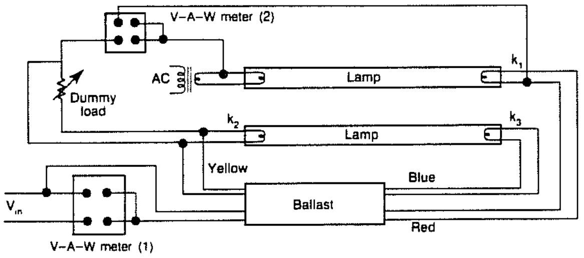
Introduction

New energy-saving devices that operate rapid-start fluorescent lamps include solid-state ballasts, current reducers, low-light-output lamps, and dimming systems. A newer technique to improve lamp efficacies is removing filament power a short time after the discharge is initiated. The input/output performance of various types of rapid-start fluorescent lamps over a range of frequencies without applied filament power has been described [1]. This paper examines the distribution of power for a two-lamp, F-40, T-12, rapid-start, cool-white fluorescent system operated with a standard Certified Ballast Manufacturers (CBM) ballast and a solid-state ballast. The change in power distribution is measured with and without filament power. The two techniques used to measure the electrical performance are described. The results are discussed in terms of ballast design options and performance trade-offs.

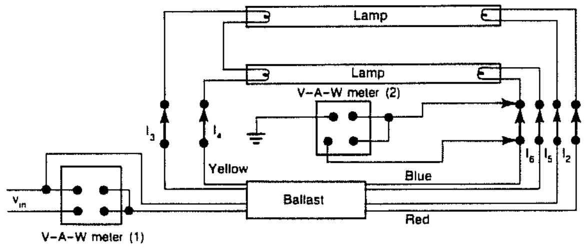
Experimental Procedures

The electrical characteristics of a two-lamp, F-40, T-12, rapid-start, cool-white fluorescent lamp system were measured under ambient conditions of 25 ±1°C. The same well-burned-in lamps (2000 hours of operation) were operated with a commercial two-lamp, F-40 CBM ballast and a commercial two-lamp, F-40 solid-state ballast. Both ballasts were designed to apply the recommended ANSI filament voltage (2.5 to 4.0 volts) during operation. Electrical measurements were made with and without full filament power. The filament power was removed by disconnecting the appropriate filament leads. The electrical parameters were measured using two types of circuits: one is designated an isolation circuit, the second is the multiport method. [2]

Electrical Circuits



(a) Isolation



(b) Multi-Port

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Figure 1. Test circuit for measuring power distribution by (a) isolation method, and (b) multiport method.

Figure 1a shows the isolation circuit used to measure the electrical input characteristics to the ballast: the lamp arc power, the input power, lamp current and voltage, and the filament voltage. The volt-ammeter-wattmeters, (V-A-Ws) are high-frequency meters that measure the true rms current and voltage as well as the power. The procedure to measure the lamp arc current requires a dummy load resistance for one electrode. In order to determine the applied filament power, the ohmic impedance of each filament must be measured. The circuit shown in Fig. 2 is used to measure the filament resistance. By switching the filament between the ballast leads and the external transformer that supplies the same filament voltage, the dummy resistor is varied until there is no measured change in input power. The value of the dummy resistance at this condition is recorded. The resistance of all four filaments was measured for the lamps operated with core-coil and solid-state ballasts.

Figure 1b shows the circuit used for the multiport measurements. This technique measures the input power, current, and voltage plus the total input power to the two lamps. The total lamp power is the sum of the power at each port. Each port power is measured with respect to the V-A-W's grounded potential.

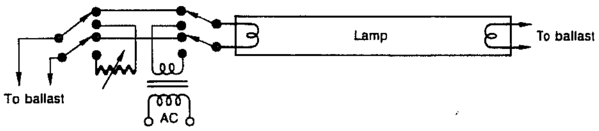

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Figure 2. Test circuit for measuring filament impedence during lamp operation.

Light Measurements

The light output of the lamps is measured with a photometer that views a portion of the total light flux. The test lamps were operated for more than 2000 hours to minimize the change in light output over testing periods. The lamps were calibrated with standard lamps measured under standard conditions in an integrating sphere. The light measurements are normalized to the lamps' initial light output, i.e., total flux output after 100 hours of operation.

Electrode Resistance

The electrode resistance, a measure of its temperature, was also measured under the two experimental conditions. Under normal operating conditions, the electrode resistance was determined by the method described above with the circuit shown in Fig. 2. When the lamps were operated with no filament voltage (one lead of the filament disconnected), an ohmmeter was used to measure the electrode resistance. The filament resistance was also measured at 0, 2, 3, and 3.5 V across the filaments when there was no lamp discharge. All four filaments for the two lamps were measured and their average value calculated.

Under each of the above conditions, the color temperature of the filaments was observed in lamps that had the phosphor coating removed at the ends.

Results

Isolation Circuit Data

Table I lists the characteristics measured with the isolation circuit for both 60-Hz and high-frequency operation. The lamp arc power was measured for each lamp and varied as shown in the table. The cathode power for each filament is given and was calculated based on the impedance measured during operation. Also given is the measured cathode voltage, shown in parentheses. The lamp power is the sum of the arc power of the two lamps and four cathodes.

The results show that when filament power is removed:

i) the input power decreases,

ii) light output remains the same,

iii) at 60 Hz the lamp current decreases, and

iv) there is no change in lamp current for the solid-state ballast system.

Six-Port Data

Table II list the results obtained with the six-port method. These measurements show the same trends as with the isolation circuit: a decrease in input power and total lamp power with no change in light output when the filament power is removed. The cathode power given in this table was measured with the isolation circuit.

There is good quantitative agreement between the two methods (within 1%) after accounting for the 2% increase in light output measured at high frequency by the multiport method.

Power Distribution

Tables III and IV present results in terms of each system's efficacy and of the power dissipated by the ballasts, filaments, and lamp arc. The ballast factors for the two systems are included.

These results can be compared to Hammer's, [1] shown in his Fig. 4. He obtains lamp efficacies of about 81 and 88 lumens per watt at 60 hertz (Hz) and 25 kilohertz (kHz), respectively, with no filament power. He measured lamp efficacy with an unmodulated sinusodial source at high frequency. The solid-state ballast we used in these measurements had a 25-kHz output that was modulated 25% at 60 Hz. We measured lamp efficacies of 80.4 and 92.2 lumens per watt at 60 Hz and 25 kHz, respectively.

TABLE I

CIRCUIT ISOLATION DATA, TWO-LAMP

FLUORESCENT SYSTEM

	60 Hz		High Frequency	
Ballast Input	**Standard**	**No Fil. Power**	**Standard**	**No Fil. Power**
Voltage (V)	120	120	120	120
Current (A)	0.808	0.778	0.640	0.597
Power (W)	95.7	91.8	70.9	66.0
Lamp Arc				
Voltage	99.7	102.4	106.7	107.3
Current	0.415	0.408	0.273	0.274
Power	35.6, 36.9	36.2, 37.3	28.6, 28.2	29, 28.5
Cathodes				
Power 1 (W)	0.8 (3.4V)		1.4 (3.5V)	
Power 2 (W)	0.8 (3.5V)		1.3 (3.5V)	
Power 3 (W)	0.8 (3.5V)		1.2 (3.5V)	
Power 4 (W)	0.8 (3.7V)		1.3 (3.6V)	
Total Lamp Power (W)	75.7	73.5	62.0	57.5
Light Output (lm)	5930	5920	5260	5290

TABLE II
SIX-PORT DATA
TWO-LAMP FLUORESCENT SYSTEM

	60 Hz		**High Frequency**	
Ballast Input	**Standard**	**No Fil. Power**	**Standard**	**No Fil. Power**
Voltage (V)	120	120	120	120
Current (I)	0.805	0.773	0.648	0.611
Power (W)	95.5	91.8	71.8	67.8
Cathode Power (W)	(3.2)	-	(5.2)	-
Port 1 (W)	+22.9	+32.5	-42.9	+15.7
Port 2 (W)	+9.0	0	60.1	0
Port 3 (W)	-38.4	-3.4	-102.1	0
Port 4 (W)	+41.1	+4.8	+131.2	+27.3
Port 5 (W)	-32.8	0	+52.1	0
Port 6 (W)	+73.1	+39.7	-35.8	+15.6
Total Lamp Power (W)	74.9	73.6	62.6	58.6
Light Output (lm)	5920	5910	5380	5410

TABLE III
POWER DISTRIBUTION WITH AND WITHOUT FILAMENT POWER AT 60 HZ

		Isolation	**Six-Port**	
	Standard	**No Fil. Power**	**Standard**	**No Fil. Power**
Ballast Input Power (W)	95.7	91.8	95.5	91.8
Ballast Dissipation (W)	20.0	18.3	20.6	18.2
Lamp Arc Power (W)	72.5	73.5	(71.7)	73.6
Filament Power (W)	3.2	0	(3.2)	-
Total Lamp Power (W)	75.7	73.5	74.9	73.6
Light Output (lm)	5930	5920	5920	5910
Ballast Efficiency (%)	79.0	80.1	78.4	80.1
Lamp Efficacy (lm/W)	78.3	80.5	79.0	80.3
System Efficacy (lm/W)	62.0	64.5	62.0	64.4
Ballast Factor	94.1	94.0	94.0	93.8

TABLE IV
POWER DISTRIBUTION WITH AND WITHOUT FILAMENT POWER AT HIGH FREQUENCY

	Isolation			**Six-Port**
	Standard	**No Fil. Power**	**Standard**	**No Fil. Power**
Ballast Input Power (W)	70.9	66.0	71.8	67.8
Ballast Dissipation (W)	8.9	8.5	9.2	9.2
Lamp Arc Power (W)	56.8	57.5	57.4	58.6
Filament Power (W)	5.2	0	5.2	0
Total Lamp Power (W)	62.0	57.5	62.6	58.6
Light Output (lm)	5260	5290	5380	5410
Ballast Efficiency (%)	87.4	87.1	87.1	86.4
Lamp Efficacy (lm/W)	84.8	92.0	85.9	92.3
System Efficacy (lm/W)	74.2	80.2	74.9	80.0
Ballast Factor (%)	83.5	84.0	85.4	85.9

TABLE V
Filament Resistance and Temperature

	Filament Voltage (V) at No Lamp Power			
	0V	2V	3V	3.5V
Filament Resistance (Ω)	2.5±.2	6.7±.5	8.8±.4	9.7±.4
Filament Temperature (°C)	(25)	(450)	(600)	(650)

	Filament Resistance (Ω) at Full Lamp Power	
	Full Filament Voltage	No Filament Voltage
Solid-State Ballast (25 kHz)	9.3 (630°C)	5.4 (300°C)
Magnetic Ballast (60 Hz)	15.7 (1100°C)	8.9 (610°C)

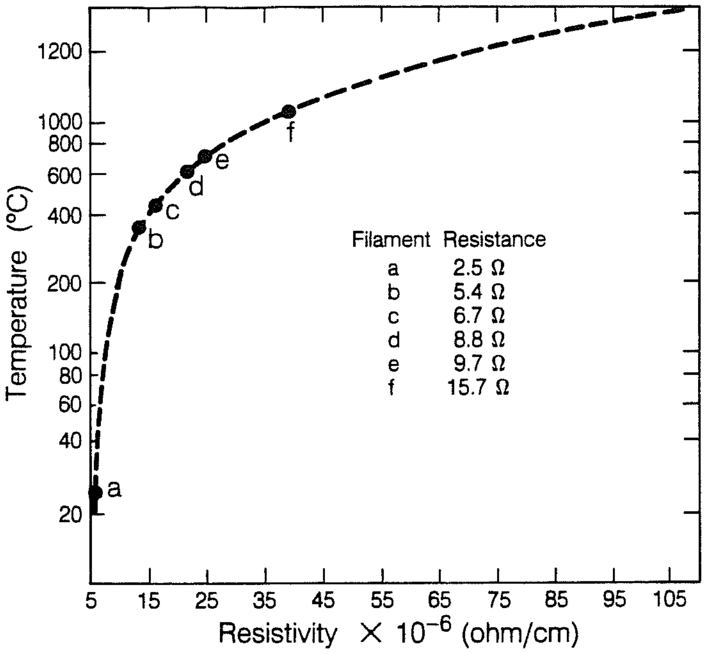

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Figure 3. Plot of Tungsten resistivity as a function of temperature.

Filament Temperature

Table V presents the measured resistance of the filaments. The values listed are the averages for all four filaments of the two lamps. From the measurement with no lamp power at zero filament power, an estimate of the length divided by area can be obtained using the relationship between resistance and resistivity, $R = \rho$ (L/A), where R is resistance and ρ is resistivity. The value of ρ at measurement temperature of 25°C is determined to be $5.65.10^{-6}$ ohm-cm[5]. Thus for R = 2.5, L/A = 0.4×10^{-6}. Using this information, we can plot a curve of T°C vs. ρ (Fig. 3). Using 0.4×10^{6} as the value for (L/A) for each measured resistance value of the filament, we can estimate the average filament temperature under each operation condition. This is not necessarily the temperature of the hot spot when the plasma is ignited, since the filament is not uniformly heated. The estimated temperatures are listed in parenthesis in Table V.

At a resistance of 8.8 ohms the filament is observed to glow (dull red) in the unexposed areas (filament not covered with rare-earth, low-work-function material). This is in agreement with the color scale of temperature between incipient red and dark red (about 600°C).

Discussion of Results

Role of Filament Voltage

Prior to igniting the discharge in rapid-start fluorescent lamps, the filaments are heated to soft-start the lamps, i.e., reducing the rms and peak starting voltage needed to ignite the discharge. This reduces the amount of alkaline earth oxides that are removed by the large cathode temperature excursion and high electric field during starting.

When operating, the filaments are heated by the cathode voltage and the flow of arc current, as well as the energy dissipated by the accelerated arc current at the anode (through the anode fall). The measurements in this study suggest that the major source of cathode heat is derived at the anode. At 60 Hz, the filament resistance is 15.7 ohm (~1100°C), while at high frequency the resistance is 9.3 ohm (~630°C), although the applied voltage is the same. The difference in the lamp operation at low and high frequency has been shown to be a reduction in the anode fall of about 10 V [3], which results in improved lamp efficacy at high frequency.

When the filament voltage is removed, the filament temperature of the lamps at both low and high frequency is reduced by about half, to about 610° at 60 Hz and about 300°C at high frequency. It is not obvious how this temperature reduction will affect lamp life, since the alkaline earth material is removed primarily by evaporation, which is reduced at the lower filament temperatures [4]. Removal by sputtering, however, increases at the lower filament temperature and arc current.

The measurements show that lamp current remains constant with and without filament power. However, lamp voltage increases when filament power is removed, due to an increased cathode voltage. This increase in cathode voltage may increase the ion bombardment of the cathode, resulting in the removal of the low-work-function alkaline earth material.

Lamp life measurements on lamps operated continuously with no filament power, compared with lamps operated 3 hours on and 20 minutes off with filament power, indicate that lamp life with no filament power is slightly reduced.[5] This suggests that the ion bombardment at the cathode becomes more prominent when the filament power is removed.

Performance Trade-Offs

Measurements show a reduction in power of 3.8 and 4.5 watts for the two-lamp system at 60 Hz and high frequency, respectively. Considering this savings for 20,000 hours of operation, at $0.075 per kilowatt hour (KWh), one finds a reduced operating cost of $5.70 and $6.75 at the two frequencies. Even assuming lamp life is reduced by 50%, removing the filament power would be cost-effective, since the cost of replacing a lamp would be less than $3 per lamp. In fact, IES lighting maintenance practices recommend relamping every two to three years (about 8000 to 12,000 hours for typical building use), which would render filament power removal still more attractive.

Dynamic and Static Dimmers

Many new devices are available to lower the light output of standard rapid-start, two-lamp fluorescent systems. Static systems lower light output by 30 or 50%. Dynamic dimmers lower the light output down to 15% of full light output. The applied lamp filament voltage is reduced by some of these systems. As the results from this study show, filament temperatures will be greatly reduced. Using systems that reduce filament power will also reduce the life of the lamps. However, if the reduction in filament temperature and arc current is not too severe, the reduction in power, hence operating cost, will generally compensate for lamp replacement costs.

Summary

One significant feature of 60-Hz and high-frequency operation of rapid-start fluorescent lamps is that filament temperature decreases at the same applied filament voltage.

Removal of the filament voltage for a two-lamp system increases system efficacy by at least 4 to 6% at 60 Hz and high frequency, respectively. With no applied filament voltages the system will provide the same light output at lower input power. The removal of filament voltage when the lamps are operating significantly reduces the filament temperature. There is evidence that lamp life will be shortened at this reduced temperature. However, the additional cost due to reduced lamp life for 60-Hz and high-frequency systems is more than compensated for by reduced operating costs.

Acknowledgement

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