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PERFORMANCE EVALUATION OF DIMMABLE LIGHTING SOURCES WITH FLUORESCENT TUBES FOR INDOOR APPLICATIONS

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ABSTRACT

In the frame of a research work aimed to analyze and optimize the lighting installations performances in offices, two papers are presented in this symposium.

In this first paper, various lighting sources with fluorescent tubes are experimentally tested in order to identify their performances, mainly their power consumption. A 20% economy in power consumption can be obtained with high grade fluorescent tubes and electronic ballasts by comparison to standard material. Dimmable electronic ballasts are especially considered and the consequence of their dimming on the performances of the lighting installation.

In a second paper, simulations will be performed using the results of this first part in order to evaluate the lighting power consumption in a typical office.

1. INTRODUCTION

The tertiary sector, essentially composed of buildings, represents more than 40% of the total energy consumption in Europe. A decrease of the European energy demand requires thus a better energy performance of buildings. Lighting installations represent a significant part of this consumption (about 35% of the total primary energy consumed in buildings like offices and schools). This justifies the aim of this work which is to analyze and optimize lighting installations performances in offices. Only lighting with fluorescent tubes (the main light source in use in this type of buildings) is addressed in this work.

Our study is twofold. In a first paper, which is here of concern, various systems are experimentally tested in order to identify their performances, namely their power consumption, in function of their using mode.

Some of the results obtained will be used in a second paper [1], devoted to perform simulations in order to evaluate the lighting energy consumption (on a yearly basis) in a typical office according to different strategies.

Modern lighting systems using electronic ballasts EB (mainly dimmable - DEB) are focussed in this study. Comparison is made with tubes driven with classical ferromagnetic ballast (FB). The luminous efficacy of the lamp (luminous flux divided by the total consumed power) is here mainly addressed.

2. MEASUREMENT METHODOLOGY

2.1 Power measurement

The main measurements of concern are related to the power consumed by the tube itself and the different auxiliaries (ballasts, control gears, sensors) depending on the dimming level (when applicable). Note that when speaking about P_{tube}, we include the power consumed by the two heaters (or filaments). Other electrical quantities as power factor, RMS voltages and currents, harmonic content are also of interest.

Figure 1 represents a tube driven by an electronic ballast (EB). We observe that the tube itself and the ballast are multi-terminals components preventing the direct measurement of the power they consume (unlike the input power to the whole system which is a two-terminal circuit authorizing the simple wattmeter connection as on the figure – the wattmeter is here represented by the traditional scheme of an electrodynamic instrument even if it is actually an electronic one). The solution is to use the '(n-1) wattmeter method' where n is the number of terminals, consisting to successively measure the power with the wattmeter sensing the current of each of the (n-1) lines and the voltage between this line and the n^{th} line taken as reference, and then to sum up algebraically these results for obtaining the searched power.

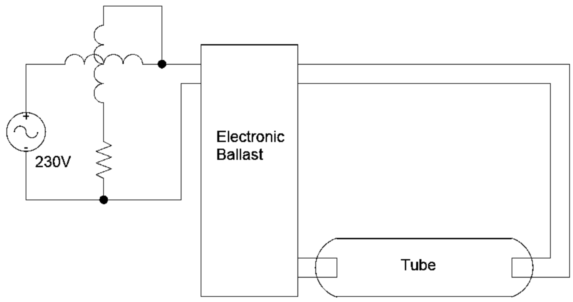

Figure 1. *EB driven tube with wattmeter in total power measurement configuration*

Figure 2 gives the way to measure the power consumed by the tube. Since this one has four terminals (the two filaments), three power measurements are needed. The *Voltech ballast CT* is an electronic current transformer, the role of which is to insure a galvanic isolation between both wattmeter circuits: it has the property of a high band-pass appropriate to 'HF' signals (see next paragraph).

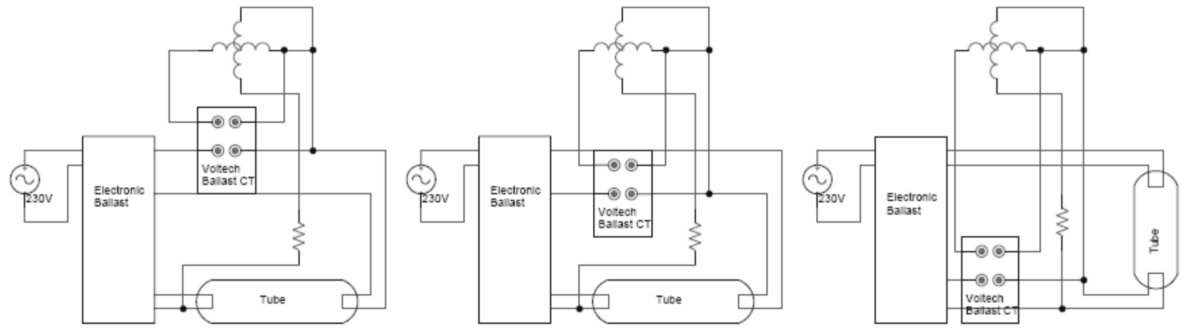

Figure 2. *Power measurement of the tube*

Another difficulty with electronic ballasts is that the frequency at the tube side is in the ultrasonic range (typically between 20 and 80 kHz depending on the dimming – we denote it as the 'HF' range). As, furthermore, the 'HF' signals are distorted, it requires the use of an instrument the band-pass of which is several hundred of kHz!

Now that the input power and the power at the tube are known, the power consumption of the ballast is simply the difference between the two former ones. This is perhaps simple but with the negative consequence of a possible poor relative accuracy on this quantity because it represents only a small fraction of the other powers. We recall that the modulus $|\rho_c|$ of the relative error on a quantity C resulting from the difference between two other quantities A and B is in the worst case:

$$|\rho_c| = \frac{A|\rho_A| + B|\rho_B|}{A - B}$$

leading to a severe relative error on C when A and B are close together.
Applying this in our case: $P_{ballast} = P_{total} - P_{tube}$ where P_{total} and P_{tube} are measured separately with a relative error $|\rho_{wattmeter}|$, the worst case gives:

$$|\rho_{ballast}| = |\rho_{wattmeter}| \frac{P_{total} + P_{tube}}{P_{ballast}}$$

If, as a realistic example, $P_{ballast}$ is about 10% of P_{tube}, we obtain:

$$|\rho_{ballast}| \approx 20 |\rho_{wattmeter}|.$$

In order for this error to be acceptable, the wattmeter error has to be very low.

The electrical quantities were measured with a digital power analyzer of rather good performances: the *VOLTECH PM100* model (www.voltech.com). It guarantees an accuracy of about 0.4% on P_{total} and only a few percent on P_{tube} (this figure is poorer due to the 'HF' signals). For the reasons explained above, the values obtained for $P_{ballast}$ are only indicative.

2.2 Flux measurement

The luminous output of the tube is very simply measured on a relative level thanks to a photo-sensor clipped at a random place on the tube and aimed to it. Note that the spectral sensitivity of the detector is here irrelevant because we can suppose that the light spectrum is independent of the dimming level. This configuration allows for instance the evolution of the luminous efficacy of a tube (in lm/W) to be evaluated in function of the dimming. But for comparison between different tubes, an absolute calibration is required. This is performed, for each lamp under study, in a classical Ulbright sphere at nominal regime of the tube. For reason linked to the age of the material used and the lack of recent calibration, it is reasonable that we don't claim for the absolute flux values (in lm) an accuracy better than 10%, which is nevertheless acceptable for this study.

3. MATERIAL UNDER TEST

3.1 - T8 *Philips* tube *Master TLD super 840–58 W*
with dimmable electronic ballast (DEB) *Philips HF-Regulator HF-R 158 TL-D*

3.2 - T8 *Sylvania* tubes
- Tube *Sylvania Luxline plus 840 – 58 W*
- Tube *Sylvania Luxline 133 – 58 W*
- Tube *Sylvania Luxline plus 840 – 36 W*
- Tube *Sylvania Luxline 133 – 36 W*

The model 840 lamp is of high colour rendering index and high efficacy (typically 90 lm/W) while the model 133 is of standard quality (efficacy of 80 lm/W)
With the following ballasts :
- dimmable electronic ballasts (DEB) *Osram-Quicktronic De Luxe HF 158 or 136 DIM*
- conventional ferromagnetic ballasts (FB) (from the brand *Vossloh-Schwabe)*

3.3 - Control gears and detectors

We also considered different control systems, including sensors combining presence detection and daylight measurement. We were essentially focussed on the solutions proposed by the Belgian company *ETAP* (www.etaplighting.com), namely the *ELS + MDD (or MDS)* systems but similar solutions exist elsewhere. Without any presence in the room, the flux is reduced to a preset value (or simply cut off); when a person enters in the detection field, the luminous flux is controlled by an analogue 1-10V DC voltage in function of the daylight (detected by a light dependent resistor) by way of a *Control-it* control unit (equivalent to *Philips LRC 1010 TRIOS light controller)*. This unit can act by luminaire or at a centralized level. A *DALI* (Digital Addressable Lighting Interface) control unit is also available for *DALI* electronic ballasts inserted in a *DALI* network.

We observed a very limited (typically about 2 W) power consumption of these control units and sensors: therefore, their contribution in the total power consumption is not taken into account: in the results below.

4. RESULTS

4.1 *Philips* ballasts

Figure 3 gives the powers in function of the luminous flux (relative to the nominal or full flux) for the *Philips* system (tube + DEB). We observe a remarkable linearity of the total power in function of the relative flux. The regression straight line is:

$$P_{tot} = 0.46\ \Phi_{relat.\%} + 9.0\ \ (W)$$

The constant term of this expression (justified by the fact that the ballast consumption is not nil even with the tube in turn-off state) leads to the conclusion that the luminous efficacy (in lm/W) decreases in function of the dimming depth. We also note that the ballast consumption is rather independent of the dimming (and close to the constant term 9.0 W), with the consequence that the power at the tube is also approximately linear in function of the flux, which is a rather foreseeable conclusion since this power is essentially transformed in radiating power which is, for a constant spectrum, proportional to the luminous flux.

4.2 *Osram* ballasts

- Osram HF 1x58 DIM

There is practically no power difference between the two types of tube (*Sylvania* 840 or 133). The regression straight line for the total power is

$$P_{tot} = 0.47\ \Phi_{relat.\%} + 8.7\ \ (W)$$

which is very close to the law obtained with the *Philips* system.

We also verified by absolute flux calibration the difference of about 13% between the flux emitted by both lamps, as expected in the data sheets.

- Osram HF 1x36 DIM

Same comments. The linear law is

$$P_{tot} = 0.29\ \Phi_{relat.\%} + 6.8\ \ (W)$$

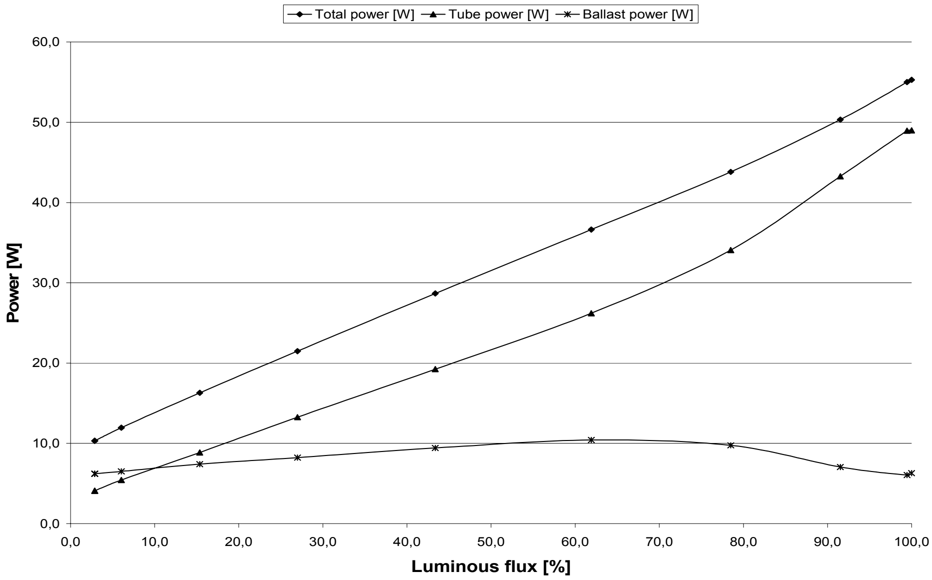

Figure 3. *Powers in function of relative flux for Philips system (HF 158 TL-D tube + ballast)*

4.3 Ferromagnetic ballasts

These conventional ballasts are of course non dimmable by a controlling (analogue or digital) access. We observe with the different models under test that generally the flux is close to the nominal flux with electronic ballasts (it means that the manufacturers guarantee a certain inter-changeability concerning the light output) but at the price of higher total power (even if the ballast consumption is also similar to the corresponding electronic models). We actually observe a decreasing in luminous efficacy of about 10% with conventional ferromagnetic ballasts which is conform to what is mentioned in the literature.

4.4 'Total power – absolute flux' linear law

The linear relationship (regression line) mentioned above for the different dimmed systems is given in Table 1 in term of the total power (in W), this time in function of the absolute flux (in lm). The data given are rounded taking into account the fact that our flux measurements are not guaranteed at more than 10%, which is appropriate for practical purposes. The higher slope with standard tube for a same nominal power is the consequence of its lower luminous efficacy. These simple formulas are very useful and as far as we know are given for the first time. They are derived from our experiments with *Philips, Sylvania* or *Osram* materials which are the dominant brands on the market but, of course, these formulas are not guaranteed for other materials.

58W high efficacy tube with ad-hoc dim. ballast	$P_{tot} = 0.0100\ \Phi(\mathrm{lm}) + 9$ (W)
58W standard tube with ad-hoc dim. ballast	$P_{tot} = 0.0114\ \Phi(\mathrm{lm}) + 9$ (W)
36W high efficacy tube with ad-hoc dim. ballast	$P_{tot} = 0.0100\ \Phi(\mathrm{lm}) + 7$ (W)
36W standard tube with ad-hoc dim. ballast	$P_{tot} = 0.0114\ \Phi(\mathrm{lm}) + 7$ (W)

Table 1. *'Total power – absolute flux' linear law*

4.5 Luminous efficacy

Figure 4 synthesizes the different results regarding the luminous efficacy in function of the luminous flux. One among the comments that we can do on this graph is that for a fixed flux, the luminous efficacy is higher for a 36W system than for a 58 W system. It is therefore preferable to install systems of lower electrical power and to use them at lower dimming depth (closer to their nominal regime) than systems of higher power but deeper dimmed.

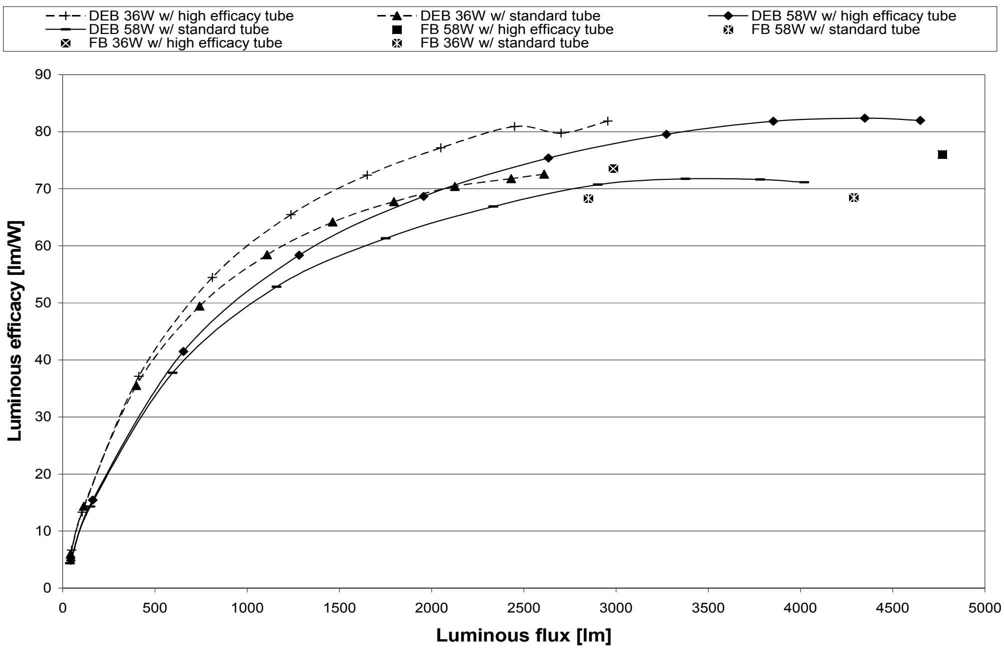

Figure 4. *Luminous efficacy (lumen/total power) versus flux*

4.6 Power factor

Recall the definition of the *power factor (PF)*:

$$PF = \frac{P}{U_{RMS}\, I_{RMS}}$$

It concerns here the input of the system 'tube plus ballast' (total power) and has to be as high as possible for optimizing the connection of the lamp to the mains. This parameter is thus also of concern when speaking about the tube performances in dimmed regime. Generally spoken, it is observed that the power factor decreases in function of the dimming depth. See Figure 5

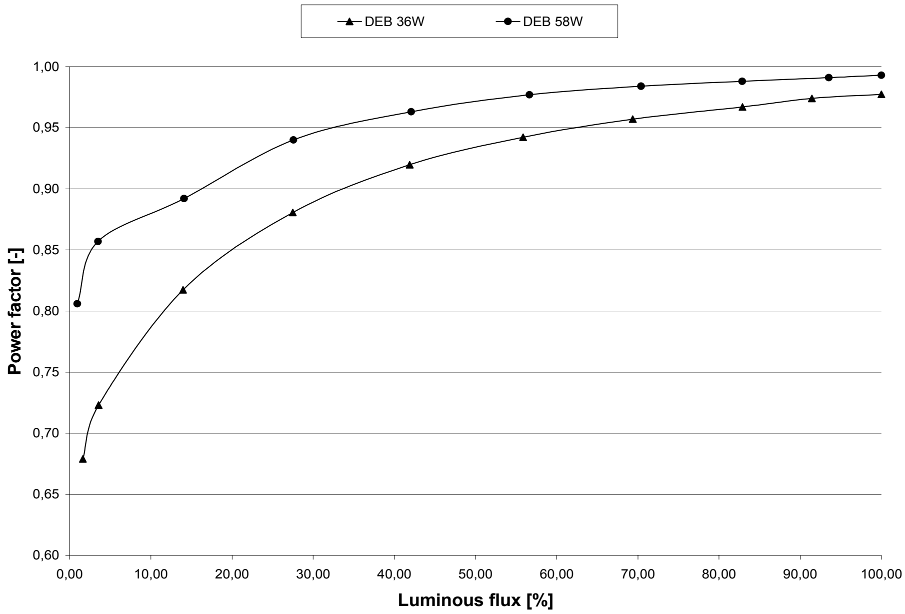

Figure 5. *Power factor versus relative flux (OSRAM ballasts)*

5. CONCLUSIONS

- Choice of high grade tubes is recommended for their higher luminous efficacy of more than 10%
- Use of electronic ballasts (EB) in place of ferromagnetic ballasts (FB) allows a reduction of about 10% of the total power consumption
- Dimmable electronic ballasts (DEB) are obligatory for light management (see [1])
- DEB's have poor performances at deep dimming (dramatic decrease in luminous efficacy, power factor and harmonic purity). If a large dimming range is not required, it is thus advisable to design the installations in order that their tubes are working near their nominal regime
- DEB's exhibit a linear relationship of their flux in function of the total power. This facilitates the study of a new installation (see [1])
- The power consumption of lighting management systems (including sensors) has a relative weak contribution to the whole power consumption.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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