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Spectroscopic and electrical study of rare-gas-based, hollow cathode luminescent discharges: Application to the lifetime and efficiency enhancement of mercury-free signs*

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Abstract: This work deals with the potentialities of mercury-free mixtures for the efficient operation of luminous signs used for publicity lighting. The experimental study of rare-gas-based, cold hollow cathode, low-pressure luminescent discharges is reported. Electrical and spectroscopic measurements are presented with a special emphasis on the radiation properties of the positive column. The best mixtures for phosphor excitation are described in terms of composition and pressure together with their sensitivity to potential fluctuations of the operating conditions during sign lifetime. Aging studies are presented, showing evidence of a strong trade-off between the output power and the sign lifetime. The selective trapping of the heavier gas present in the gas mixture is presented and proven to be at present the main reason for the sign lifetime limitation. The limitation of commercial (sinusoidal or square waveform) ballasts for the excitation of such mercury-free discharge is presented. Finally, preliminary measurements, performed using a lab-developed short rise time and low duty-cycle driver, are reported, showing a significant increase of the illuminance and efficiency (up to a factor three) of mercury-free signs as compared to the values obtained with conventional excitation.

Keywords: mercury-free lamp; fluorescent lamp; glow discharge; UV–VUV spectroscopy (ultraviolet–vacuum ultraviolet spectroscopy); pulsed discharge; xenon resonance line.

FRAMEWORK AND MOTIVATIONS

This work deals with the development of new environmentally friendly luminous signs. The sign operation relies on the production of a low-pressure glow discharge in a glass tube equipped with two cold hollow electrodes. The glass tube, the typical length of which varies from a few tens of centimetres to a few metres and the diameter of which is of a few tens of millimetres, is generally filled with a neon, neon–argon, or neon–argon–mercury low-pressure mixture. Except for some of the signs radiating in the red spectral domain, the glass tube has its interior surface coated with a phosphor layer. This phosphor layer emits light in the visible domain when excited by mercury ultraviolet radiation lines. All the critical parts of signs have been optimized for tens of years to achieve the best efficiency (i.e., ratio of

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the light output flux to the injected power), a long lifetime, a good operation from –20 to +40 °C, and a limited chromatic variation during sign lifetime. The phosphor chemical composition and the electronic ballasts have been specially designed to obtain efficient glow discharges in neon–argon–mercury mixtures.

Unfortunately, mercury is a hazardous species and a large effort is nowadays devoted to find out technological issues for its substitution, not only in signs, but more generally in all fluorescent lamps. The possibility of mercury substitution in luminous signs used for publicity lighting, has been studied through a three-year research program initiated in 1999 by the AUPEM-SEFLI Company*. The different industrial partners and research laboratories involved in this R&D project, labeled as Dynalum, worked on the two main regions of the glow discharge, i.e., the nearby electrode zone and the positive column.

The CPAT** laboratory essentially studied the electrode region and measured the cathode fall, the breakdown voltage amplitude, and the second Townsend coefficient in mercury-free mixtures of various compositions and pressures [1]. The positive columns produced in these mercury-free discharges were studied in the GREMI laboratory to measure their efficiency for phosphor excitation. The development of new environmentally friendly signs appeared as a highly cross-correlated problem, the determination of the more efficient mercury-free mixtures relies on the simultaneous consideration of the two region features.

In this paper, the positive column radiation properties of rare-gas-based mixtures experienced in GREMI are presented. The next section describes the experimental set-up used for the production and diagnostics of mercury-free luminescent discharges. The main results concerning the phosphor excitation in various rare-gas-based mixtures are then discussed. The next section summarizes the aging studies performed on signs filled with two, three, and four rare-gas mixtures. Finally, recent experimental results obtained out of the Dynalum project and dealing with the limitation of the sinusoidal or square wave current waveforms delivered by the ballast used for commercial signs (using mercury) are presented. The potentialities of a new type of electronic driver developed in GREMI and allowing pulsed excitation of mercury-free signs is also discussed in this section.

EXPERIMENTAL SET-UP

The experimental set-up articulates around four main assemblies presented in Fig. 1 and described in the following: specially designed glass tubes, a gas handling device, an industrial neon tube bombarder, and a spectroscopic and electrical diagnostic set-up.

Different glass tubes of various lengths (from 10 to 120 cm) and inner diameters (13, 18, and 25 mm), whose interior surface was coated with different phosphor sections, equipped with two hollowed electrodes and an evacuation port have been used. This evacuation port is connected to the gas handling device, the neon tube bombarder, and the spectroscopic tools.

The gas handling device allows the filling of the glass tube with a mixture containing up to five different high-purity gases whose partial pressures are controlled through mass flow controllers and needle valves. The mixture pressure was measured with a Baratron gauge. In this work, the pressure was varied from a few hundredths of mbar up to a few tens of mbar.

The large number of parameters (filling gas, nature of the gas mixtures, mixture pressure and, partial pressures) to be studied over an extended range, imposes to perform the experimental measurements in gas flow conditions. Nevertheless, the results obtained through this experimental study have been cross-checked by measurements performed on signs filled with the selected gas mixtures and sealed by AUPEM SEFLI. The sealed tubes have furthermore been used for aging studies.

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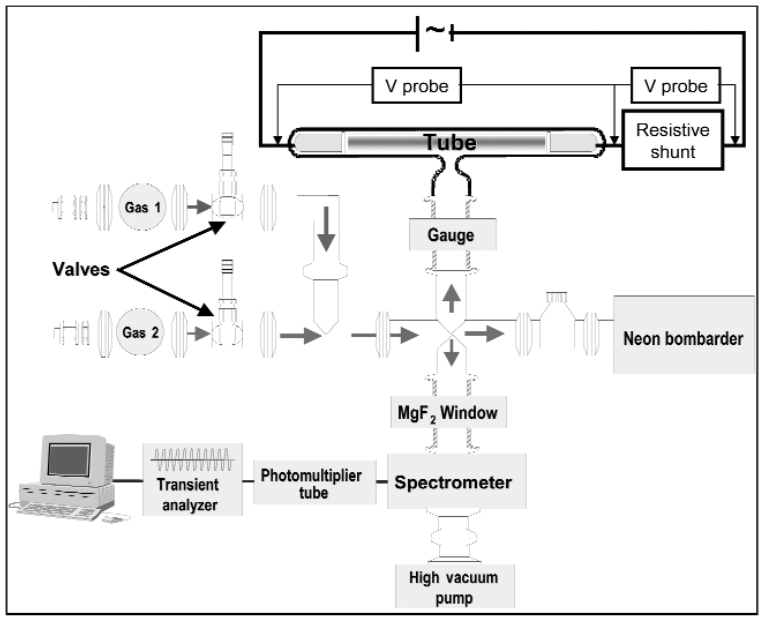

Fig. 1 Experimental set-up used for mercury-free luminescent discharge production and characterization.

The "neon tube bombarder" is the assembly used to evacuate the tube, with a turbo molecular vacuum pump, and to heat the tube up to a few hundreds of degrees to remove most of the impurities imprisoned in the electrodes and glass vessel, using a high-power transformer connected across the electrodes.

The evacuation port of the glass tube is finally connected through an MgF_2 window to a VUV–UV–vis spectrometer (Acton Research Co. VM 504) equipped with two gratings (300 and 1200 grooves/mm) covering the spectral range ranging from 110–900 nm. The spectrometer output is either connected to different photomultiplier tubes (Hamamatsu R955, R1080, and R1220) or an ICCD camera (Princeton Instruments). For electrical measurements, high-voltage probes (Tektronix P6015A, Elditest GE 3421) are connected across the discharge tube and a resistive shunt allows the record of the current flowing in the tube.

Except for measurements reported in the section dedicated to the pulsed excitation, the discharges were powered either by a 50 mA, high-voltage (3.5 kV) AC transformer operating at 50 Hz or a 50 mA, high-voltage (4.5 kV) electronic ballast operating at 25 kHz.

A Chroma meter (Minolta xy-1) was also used to measure the illuminance Y (expressed in Lux) and the chromaticity coordinates (x and y) as defined by the CIE 1931 chromaticity diagram.

PHOSPHOR EXCITATION IN RARE-GAS-BASED MIXTURES

Emission spectra

The goal of the research program was to study the potentialities of mercury-free and more restrictively environmentally friendly mixtures. The excitation of phosphors in the laboratory glass tubes was performed using the VUV light emitted by discharges produced in all the rare gases (He, Ne, Ar, Kr, Xe) and their mixtures. As neon presents the lowest breakdown voltage [2], it was used as a buffer gas in the mixture. The addition of molecular species in the glow discharge plasma leads to a strong heating of the tube (up to about 100 °C) through the population of the vibrational levels and was thus rapidly rejected for practical application.

Figure 2 presents the emission spectra of a glass tube coated with a phosphor radiating in the green spectral domain and flowed with neon, neon–argon, and neon–xenon mixtures. For these three discharge conditions, the neon pressure and the mixture pressures are the same and equal to 2 mbar. The argon and xenon partial pressures are also the same and equal to 0.1 mbar.

The Ne/Xe mixture appears as the most efficient for the excitation of the green phosphor. For the pressure and mixture compositions used in this experiment, the phosphor excitation achieved in Ne/Xe and Ne/Ar discharges is, respectively, 2.2 and 1.6 times that obtained in a pure neon discharge. The same result was recorded for all the other phosphors used in this work. The phosphors used in this work are the same as those used in signs containing mercury, which means that they present a high efficiency when excited by UV mercury radiation, mainly the 253.7-nm mercury resonance line. As will be described in this paper, the excitation of the phosphors in mercury-free tubes relies on the production of the VUV rare-gas resonance lines. The wavelength of these resonance lines is shorter and shorter as the atomic number of the rare gas decreases. This probably explains to a large extent that the resonance lines of the xenon are much more efficient than those of argon or neon for the phosphor excitation. In this work, green, red, and blue phosphors developed for the panel plasma display technology have also been tested. They exhibit a 30 % higher efficiency in comparison with phosphor usually employed in mercury-based signs when excited by rare-gas-based discharges. In the Dynalum program, no other specific studies have been devoted to the phosphor nature, but it must be pointed out that there exists a strong interest for new efficient phosphors excited by whether high- or low-pressure xenon discharge [3].

Discharges in pure xenon allow rather intense phosphor emissions, but the xenon breakdown voltage is the highest of the rare gases leading to a reduction of the efficiency. The discharges in pure xenon also exhibit instabilities, mainly moving striations, which appear randomly during the sign operation and lead to undesirable flickering effects.

It must also be noted that the intense visible radiations of the neon are quenched when adding a heavier rare gas in the discharge. The binary mixture plasma radiation essentially originates from the heavier rare gas in both the visible spectral domain, as shown in Fig. 2 for argon and xenon, but also in the VUV region as described in the next section. This implies that the chromatic coordinates of the tube depend mainly on the emission spectra of the phosphor and the heavier gas used in the mixture. The intensity ratio of the visible lines to the resonance lines can be varied when changing the mixture pres-

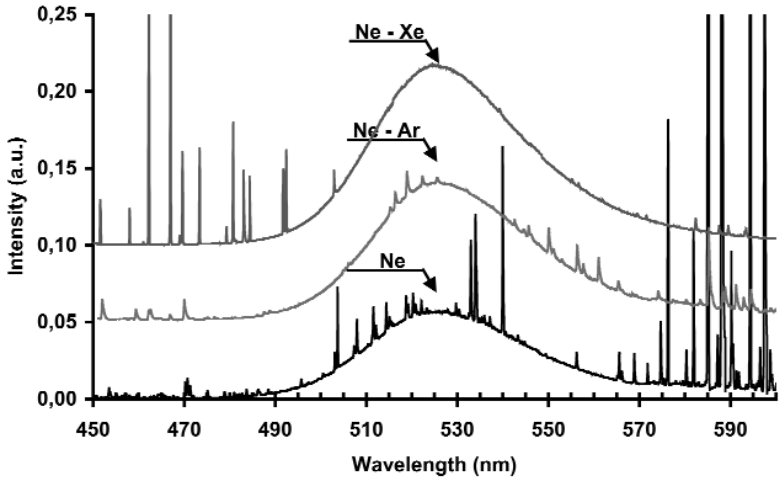

Fig. 2 Emission spectra of a green phosphor-coated glass tube flowed with pure neon, a Ne/Ar mixture (95/5) and a Ne/Xe (95/5) mixture. In the three experiments, the filling gas pressure is of 2 mbar. An offset of 0.05 and 0.1 was respectively applied to the spectra of Ne/Ar and Ne/Xe, respectively, for clarity.

sure or the current applied to the discharge tube. This might be of interest to adjust the chromatic coordinates of the signs as was reported in [4] for neon krypton mixtures. Such an optimization of the VUV to visible emission ratio was already reported in the patent literature [5] as a key solution for the development of an amber mercury-free vehicle lamp.

Phosphor excitation by the xenon resonance lines

In the pressure range investigated in this work, the VUV spectroscopic investigation of the Ne/Xe mixtures leads to the recording of both the 147-nm (Xe $3P_1$) and 129.6-nm (Xe $1P_1$) resonance lines. Figure 3 presents the evolution of these two VUV line intensities as a function of the xenon partial pressure in a Ne/Xe binary mixture. No spectral sensitivity correction was applied to the spectroscopic data obtained in this work.

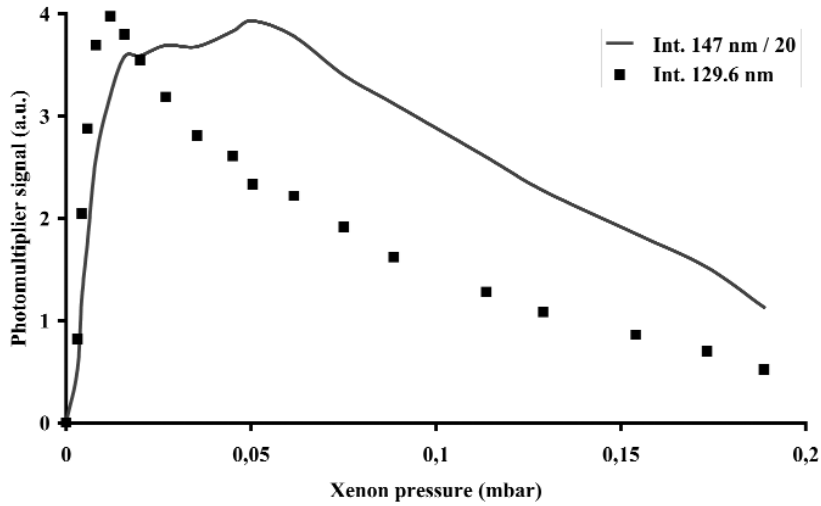

Fig. 3 Evolution of the Xe resonance lines [129.6 nm (squares) and 147 nm (line)] vs. the xenon partial pressure in a Ne/Xe binary mixture at 1.1 mbar. The intensity of the 147-nm line was divided by a factor 20 to allow the comparison with the 129.5-nm line.

The main contribution to the phosphor excitation is the 147-nm resonance line except for the low xenon partial pressures for which the 129.6-nm line has to be accounted. In a previous publication [6], we have shown that the phosphor emission intensity can be fitted by a numerical combination of the two xenon resonance line contributions as a function of pressure. The experimental set-up used in this work does not allow the measurement of the Ne VUV lines at 73.6 and 74.4 nm. The phosphor emission for extremely low concentrations of xenon in Ne/Xe binary mixtures is nevertheless partly due to the neon VUV excitation.

For the highest xenon pressures, the 147-nm line intensity decreases and consequently the phosphor emission, too. This decrease of the phosphor emission intensity is attributed both to the self-absorption of the Xe 147 nm line and to the formation of molecular states. Figure 4 presents the normalized resonance line spectra emitted by a 1 mbar Ne/Xe plasma containing 0.04 mbar and 0.17 mbar of xenon.

The spectrum measured for the higher xenon concentration (0.17 mbar) exhibits an extended red wing traducing the population of highly excited molecular states of dimer (Xe_2). For higher xenon pressure, the population of these excited states of the Xe_2 molecule results in the emission of the so-called first continuum. In our experimental conditions, this continuum radiation is not intense enough to have practical application in sign technology.

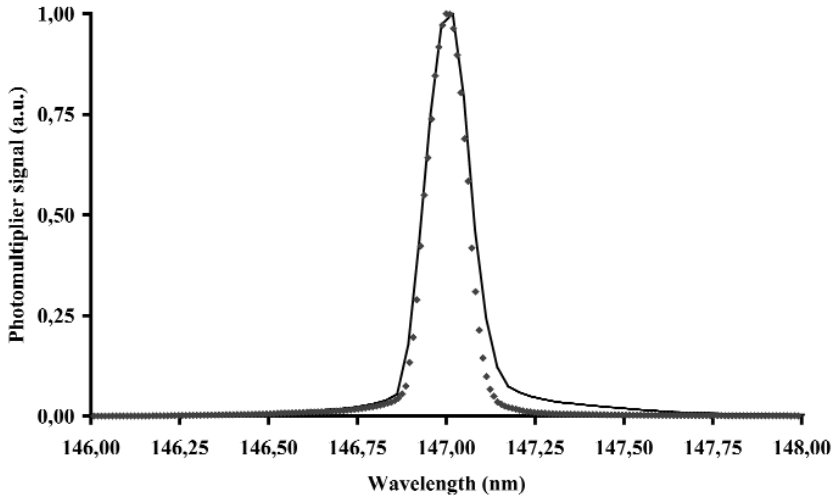

Fig. 4 Spectra of the 147-nm Xe line emitted by a 1-mbar Ne/Xe mixtures plasma containing 0.04 mbar (dots) and 0.17 mbar (line) of xenon.

While both radiation trapping and molecule formation should not limit the phosphor excitation, the quenching of the resonance atoms and the excited molecular states (Xe_2*) by collisions with the mixture species and/or the glass and metal surfaces appears as a very effective path for the plasma relaxation.

Evolution of the phosphor emission versus the mixture pressure

Figure 5 presents the evolution of the normalized phosphor emission in Ne/Ar, Ne/Kr, and Ne/Xe mixtures vs. the mixture pressure. These measurements were performed to quantify the sensitivity of the discharge to the pressure. Figure 5 illustrates that the best conditions for phosphor excitation correspond to low-pressure filling. It appears also that the pressure range corresponding for instance to the emission of at least 75 % of the maximum output obtained around one mbar is smaller when using the heavier rare gas in combination with neon.

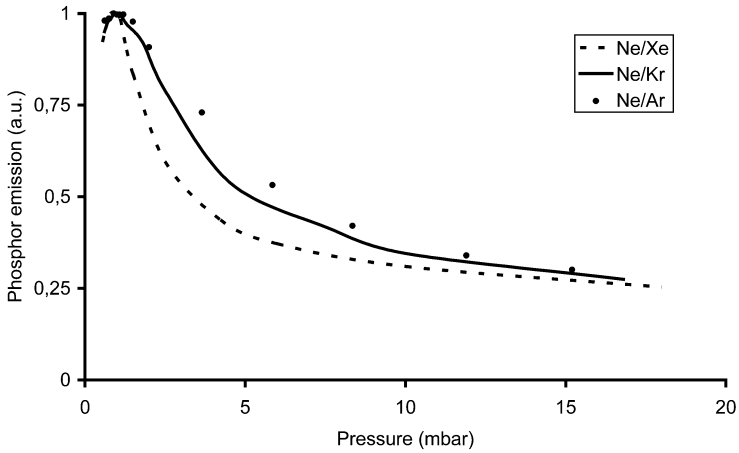

Fig. 5 Evolution of the phosphor emission intensity with the pressure in binary mixtures of Ne/Ar (dots), Ne/Kr (full line), and Ne/Xe (dotted line). The Ar, Kr, and Xe concentrations were kept to a constant value of 5 % in these experiments.

Figure 6 presents the evolution of the phosphor emission intensity in Ne/Ar, Ne/Kr, and Ne/Xe binary mixtures vs. the Ar, Kr, and Xe partial pressure. In these experiments, the mixture pressure is kept constant to 1.15 mbar and is the same for all of the three mixtures. As will be shown in the next section, the partial pressures may vary during the sign lifetime. It is thus worthwhile to be able to predict the evolution of the sign illuminance during time.

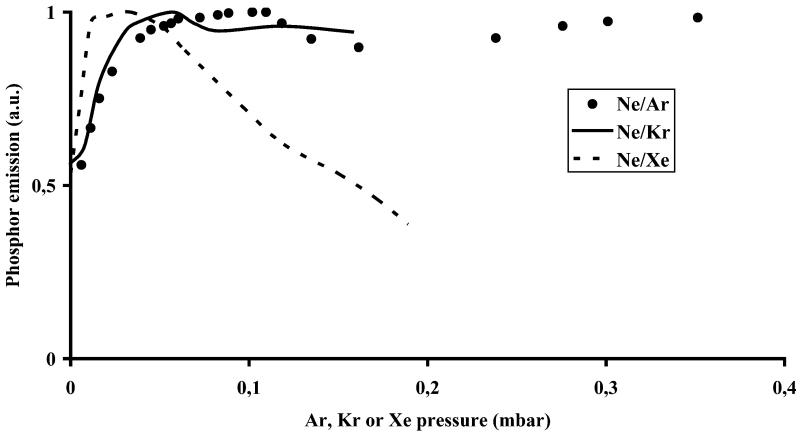

Fig. 6 Evolution of the phosphor emission intensity vs. the Ar (dots), Kr (full line), and Xe (doted line) partial pressure in binary mixtures with neon. For the three cases, the mixture pressure is of 1.15 mbar.

Figure 6 exhibits the same behavior as that depicted in Fig. 5, i.e., the more sensitive mixture appears to be the Ne/Xe one. The phosphor emission appears to be strongly dependent upon the xenon partial pressure. On the contrary, the Ne/Ar mixtures provide a very stable phosphor excitation on an extended range of partial pressure. This feature will be confirmed by the results presented in the next section and might be interesting to develop long-lived signs, but as shown in Fig. 2, emitting a less intense visible flux than for Ne/Xe mixtures. In Fig. 6, the phosphor emission intensity measured when the Ar, Kr, and Xe partial pressure is zero corresponds to the phosphor excitation by a pure neon discharge.

AGING STUDIES

As already explained, the determination of the gas mixtures likely to provide the best phosphor excitation have been performed in glass vessel flushed with high-purity gases. While we use a commercial neon bombarder and high-purity gases, it has been impossible to simply close the valve connected to the evacuation port to perform some aging studies in closed tubes. Proceeding in this way leads to an extremely fast contamination of the gas mixture by impurities and consequently a dramatic change in discharge conditions. A very fast contamination has been observed of the mixture by nitrogen molecules whose vibrational excitation leads to a very fast heating of the gas, electrodes, and glass tube. Furthermore, the aging studies should be representative of the external conditions in which the signs operate, i.e., variation of the outside temperature, humidity, etc. For these reasons, sealed tubes, filled with Ne/Xe binary mixtures, have been realized by AUPEM-SEFLI. Aging studies have then been performed partly by the industrial partner following the procedure used for commercial signs and partly in the GREMI laboratory.

The first aging studies were performed on the Ne/Xe mixtures leading to the highest illuminance, i.e., low pressure and low xenon partial pressures. Lifetimes ranging from a few hours to a few tens of days have been observed in this case. A very fast selective trapping of xenon has been measured together with very strong sputtering of the electrodes. The experimentally observed sputtering of the elec-

trodes for very low xenon concentration is in agreement with the electrical measurements and modeling studies performed at CPAT [7]. It was measured that low xenon concentration Ne/Xe mixtures present the highest cathode fall. In this case, the ion and neutral species bombarding occurs with species of high energy, undergoing a fast destruction of the cathode material. Thus, for low-pressure sign, the sputtering of the cathode leads to the deposition of metal on the tube wall in the vicinity of the electrode likely to undergo some crack in the glass tube and leading to a catastrophic end of operation of the sign. For slightly higher-pressure filling conditions, the electrode sputtering and the xenon trapping are reduced so that the sign finally operates as a pure neon tube. As a consequence of the trapping of xenon atoms during the sign lifetime, the discharge gradually tends to operate in pure neon, but the low efficiency of pure neon discharge for phosphor excitation and the very intense emission of red lines of neon lead to a complete change in the chromatic coordinates.

The second aging studies have been performed with signs filled with higher-pressure Ne/Xe mixtures, typically higher than 5 mbar. In this case, lifetimes up to 15 000 h have been measured, but as depicted in Fig. 5 with lower illuminance value. For these higher-pressure signs, the selective trapping of xenon was also evidenced, but on a much longer time scale.

Considering the results presented in Figs. 5 and 6, a third class of signs has been tested consisting of ternary or four constituent rare-gas mixtures. In this latter case, it was measured that the same lifetime value, up to 15 000 h, can be obtained as for Ne/Xe mixtures.

Figure 7 presents the spectroscopic measurements performed on a Ne/Ar/Kr/Xe-filled sign during about 300 h. The mixture pressure is of 2 mbar and the sign was powered by a 25 kHz, 50 mA, 4.5 kV transformer. The sign filling was selected to obtain a fast evolution of the discharge properties during time. This experiment started 240 h after the ignition of the sign. The spectroscopic measurements have been performed using an ICCD camera connected to the output of the spectrometer. Spectra have been recorded with an average time step of about 10 h. From these spectra, the Ar (420.1, 696.5, and 763.5 nm), Kr (431.9, 587.1, and 760.1 nm) and Xe (462.4, 467.1, and 823.2 nm) line intensity evolutions as a function of time have been plotted and fitted in Fig. 7. For each of the three gases, the three selected lines exhibit the similar amplitude evolution with time. For this reason and for the clarity of Fig. 7, the experimental data points for each gas (Ar, Kr, and Xe) represent the average value of the three selected wavelength behaviors. At the sign ignition, all the positive column radiation occurs in the

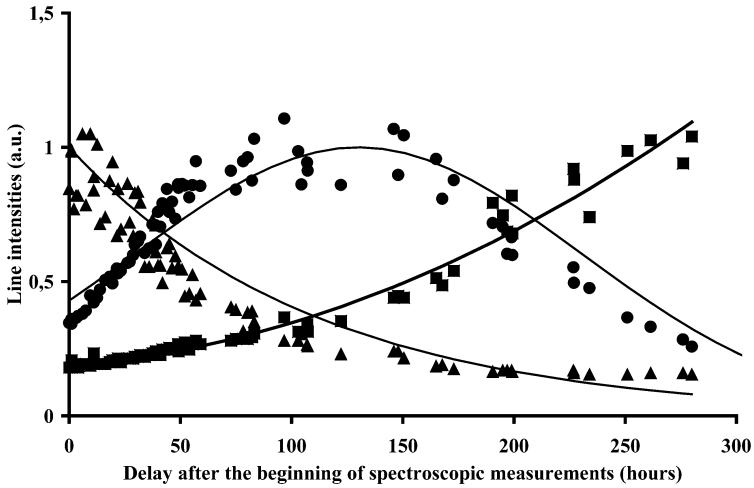

Fig. 7 Fits of the Ar (420.1, 696.5, and 763.5 nm), Kr (431.9, 587.1, and 760.1 nm) and Xe (462.4, 467.1, and 823.2 nm) line intensity evolutions as a function of time. Ar, Kr, and Xe average behavior (see text) are respectively represented by the squares, dots, and triangles. The sign was ignited 240 h before the spectroscopic measurement started. The mixture (Ne/Ar/Kr/Xe) pressure is of 2 mbar.

xenon lines, which gradually decrease with time as depicted by the xenon data fit in Fig. 7. This decrease of the xenon line emission is attributed to a trapping of xenon in the glass tube elements as was observed in Ne/Xe binary mixtures. Then, as the xenon concentration becomes very low, the krypton lines start to increase to get maximum about 130 h after the spectroscopic measurement started. The selective trapping of Kr is then measured as depicted by the decrease of the Kr lines in Fig. 7 up to 260 h. After 500 h of operation, the sign is mainly filled with a Ne/Ar mixture and the main radiation of the positive column occurs in Ar transitions.

This experiment shows evidence of the successive selective trapping of the heavier gas remaining in the glass tube during sign operation. It has been measured that the xenon trapping can be slowed in ternary or four constituent mixtures by adjusting the partial pressure of the different gases introduced in the mixture. Work is in progress to determine the best mixture conditions to enhance the sign lifetime up to 20 000 h, this value being at present that of mercury-based devices.

PULSED EXCITATION OF MERCURY-FREE SIGNS

One of the main differences between mercury-based and -free signs is the dependence of the phosphor emission intensity vs. injected power or current. For mercury-based devices, the phosphor emission intensity is a linear function of the current of the discharge from a few mA to a few hundreds of mA. The dependence of the phosphor radiation with current for a Ne/Xe sign is presented in Fig. 8. In this experiment, sinusoidal transformers operating at 50 Hz and delivering respectively mean current of 50, 100, and 200 mA have been used.

It appears that above 50 mA, the phosphor emission is constant, while that of the 823.2-nm Xe line increases with the current. Such an observation was very recently reported for He/Xe direct current (dc) positive column plasma [8]. In this paper [8], the xenon resonant level density was shown to exhibit a significant enhancement for current ranging from 20 to 100 mA, while being quite constant for higher current amplitudes up to 200 mA. As the phosphor intensity is connected with that of the Xe resonance lines, this result indicates that as the current increases, the upper states of the resonance lines are strongly connected through electron collisions with some higher energy levels of xenon. The population of these higher levels and their successive relaxation is then responsible for the increase of the xenon infrared radiations as the current increases as shown in Fig. 8. This two-step excitation of the infrared lines of xenon was previously modeled for dc positive xenon column discharge plasma [9].

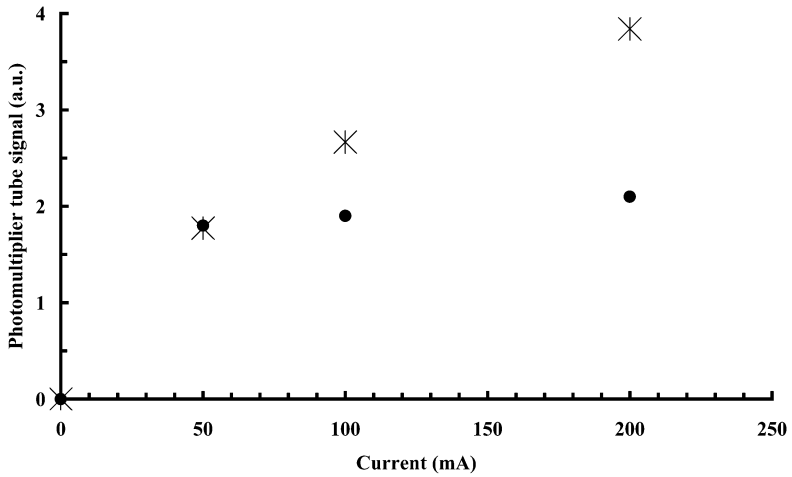

Fig. 8 Evolution of the phosphor emission (dots) and Xe line at 823.2 nm (crosses) intensities with the current amplitude.

The same effect was also measured with square current waveforms delivered by electronic ballast operating at 25 kHz.

It was estimated that with conventional power supplies, the mercury-free sign illuminance is five time smaller than that of mercury-based signs for the smaller injected power and this ratio increases dramatically as the mean current value increases. For this reason and because, in our opinion, no low-pressure gas mixture excited in a conventional way is likely to lead to a significant increase of the illuminance, preliminary experiments have been performed to evaluate the potentialities of pulsed excitation. Such investigations were previously reported for pure xenon positive column excitation [10]. In those studies [10], the pulsed excitation corresponds to square waveforms with duty cycle ranging from 10 to 50 % and a 100-kHz operating frequency. In that case, the main conclusion was that the benefit of pulsed excitation compared with direct current excitation was small when dealing with the 147-nm output performance.

In this work, a lab-developed power supply delivering short current pulses at frequency ranging from a few hertz up to 40 kHz was used to excite a sealed glass tube filled with a ternary rare-gas mixture (He/Ne/Xe) at a pressure of 5 mbar. The duty-cycle value ranges from a few tenths to a few percent. The rise time of the current pulse is shorter than 200 ns, whereas its duration is in the microsecond domain. Figure 9 presents the evolution of the phosphor emission intensity as a function of the power delivered across the tube using the pulsed power supply and a square waveforms excitation. The power delivered to the tube is calculated as the integration of the voltage waveform measured across the discharge tube multiply by the current waveform collected across a resistive shunt (see Fig. 1).

The evolution of the phosphor intensity vs. the injected power is completely different for pulsed and square waveforms excitation schemes. No saturation of the illuminance when the power is increased is measured in pulsed excitation. The efficiency of the sign is increased by a factor of three when using pulsed excitation in comparison with square waveforms excitation.

This significant enhancement of the xenon VUV emission intensity using pulsed power excitation was previously reported [5] for pure neon smaller-diameter tubes, excited by pulse current of the same duration range (microsecond time scale). In this latter case, the neon lamp efficacy was increased by 50 to 70 % in comparison with sinusoidal excitation. The best current pulse was shown to consist in a leading spike to generate neon ultraviolet radiation and a trailing pulse to increase the visible neon emissions [5].

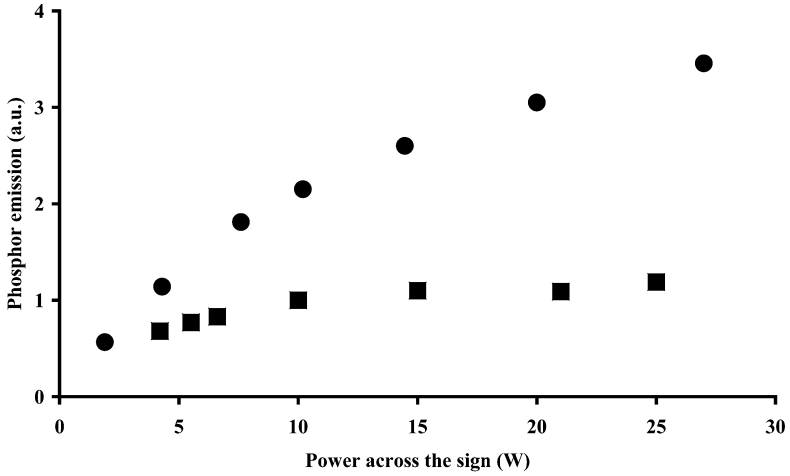

Fig. 9 Evolution of the phosphor emission intensity as a function of the power delivered across a 5-mbar mercury-free sign (filling mixture He/Ne/Xe) for pulsed excitation (dots) and square waveforms excitation (squares).

In the preliminary experiments reported in this paper, the significant enhancement of the sign efficacy results from the simultaneous increase of the VUV xenon radiation and the neon and xenon visible transitions. The main reason for these discharge changes is thought to lie in the rather different electron temperature obtained in pulsed and conventional excitation. In pulsed excitation, the current cut-off allows a fast decrease of the electron temperature and then a significant population of radiative states during the afterglow. This evolution of the electron temperature is not achieved in conventional (sinusoidal or square) excitation or is reduced in pulsed excitation if the duty cycle is too high, as was probably the case in [10].

CONCLUSION

The experimental study of rare-gas-based mixture excitation in cold hollow cathode, low-pressure signs has been performed. Using both 50- and 25-kHz conventional ballasts, the mixture pressure and composition have been optimized to achieve the highest fluorescence of the phosphors usually used in publicity lighting. Xenon appears as the best candidate to replace the mercury in such devices.

In this work, the efficiency denotes the ratio of the visible emission to the injected electrical power to the whole tube (positive column and electrode regions). The best efficiency was measured for the Ne/Xe binary mixtures in comparison with any Ne, Ar, Kr, and Xe combination. This results from both the low breakdown voltage of neon and the "long" wavelength emission of xenon resonance levels (147 and 129.5 nm) in comparison with other lighter rare-gas VUV transitions.

While being the best for phosphor excitation, the Ne/Xe mixture was also measured to be the more sensitive, in comparison with other binary rare-gas mixtures, to any potential fluctuation of whether the xenon partial pressure or the mixture pressure. The best Ne/Xe mixtures in terms of VUV production efficiency has been shown to be the low-pressure (below 5 mbar) and low xenon concentration (a few percent) mixtures.

Aging studies have been performed in signs sealed by AUPEM SEFLI and filled with the best Ne/Xe mixtures, some higher-pressure Ne/Xe mixtures, and some ternary and four constituent rare-gas mixtures. A very strong trade-off between the lifetime and illuminance has been measured during these aging studies. Lifetimes ranging from a few hours and up to 15 000 h have been respectively measured for signs filled at the best Ne/Xe mixture composition and some higher-pressure Ne/Xe filled signs, respectively. The illuminance of such higher-pressure mixtures is roughly half of that of the best Ne/Xe mixtures. The main reason for the end of the sign operation has been shown to be the selective trapping of the xenon during time. This selective trapping of the xenon appeared to be essentially monitored by the xenon content at the sign ignition for a given operating current. Lifetimes of about 10 000–15 000 h have also been measured in ternary and four gas mixtures. The selective trapping of the heavier rare gas remaining in the gas mixture has also been measured for four constituent filled signs.

Unfortunately, pure xenon discharges, for which xenon depletion during time would not be so dramatic, present a reduced efficiency and exhibit moving striations appearing randomly during sign operation.

Preliminary results dealing with the comparison of conventional (sinusoidal or square waveform) excitation with pulsed operation show evidence of a significant enhancement of the sign output power when using pulsed excitation. In this work, the pulsed excitation refers to the application of microsecond current pulses having a rise time shorter than 200 ns and delivered at operating frequencies up to 40 kHz. The saturation of the visible output power of mercury-free signs vs. the injected electrical power recorded when using conventional excitation was shown to be shifted to higher injected power in the case of pulsed excitation. As a consequence, the illuminance and efficiency of mercury-free signs is two to three times higher than that obtained with sinusoidal or square waveform excitation for injected powers typical of mercury-based devices. Work is now in progress to optimize the pulsed excitation scheme with some special attention to the current rise time, pulse duration, and operating fre-

quency. A new analysis of the best gas mixture pressure and composition is also planned in pulsed excitation regime.

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