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Helical instability in metal halide lamps under micro and hypergravity conditions

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The onset and rotation frequency of a helical instability in a metal halide lamp is studied for gravity conditions varying from microgravity to 1.8g during parabolic flights and at microgravity in the International Space Station. The results show that gravity-induced convection seriously alters the onset and behavior of the instability. Hypergravity and low lamp power increase the rotation frequency of the instability, which seems independent of the arc pressure. At microgravity conditions, only arc bending and no rotation has been observed. The arc bending increases with lamp power, allowing one to monitor the driving and damping forces of the instability. © 2006 American Institute of Physics. [DOI: 10.1063/1.2181198]

Helical instabilities in arc discharges have been elaborately studied by Mentel1 for low current densities at atmospheric pressure. The instability is driven by the self-induced magnetic field of the arc and is observed as a stable or rotating helixlike structure. Gaede2 and Ragallar et al.3 extended the theory to high-pressure arc discharges. Also, the existence of helical instabilities in high-pressure metal halide lamps has been known for some time,4 but quantitative understanding of the conditions under which they occur appears to be rather limited. Over the last decade, these lamps have become increasingly more popular due to their high efficiency and good color rendering properties.5 A poor understanding of the instabilities, which are seen as a flickering of the lamp, seriously limits further development of such energy efficient light sources. The experiments presented here will help in further understanding the nature of the instability and the forces involved, and can be used to quantitatively verify any model results.

A metal halide discharge lamp, shown in Fig. 1, is essentially a high-pressure (up to several tens of bar) Hg arc discharge.6 In addition to the Hg, which is the main species, a small amount of a metal halide salt is added. Examples of such salts are sodium iodide, thallium iodide, and various other rare earth iodides. In many cases, the salts used have a high melting point, which implies that they enter the plasma volume as a saturated vapor, with its partial pressure dependent on the coldest spot in the lamp, which is between 1000 and 1500 K. Toward the arc center, with a temperature of 5000–6000 K, the halide molecules dissociate and the metal atoms are excited and ionized. Excited rare-earth metal atoms and ions typically are extremely strong radiators in the visible, which explains the high efficiency of lamps containing these species.

Another characteristic of such high-efficient arcs is the tendency toward arc constriction, which can lead easily to arc instability. Such instabilities are driven by the induced magnetic field of the arc current. In equilibrium, this results in a symmetric radially confining force on the arc. However, any small arc displacement will result in an inhomogeneous arc current, with a higher current density near the center. This inhomogeneous current distribution results in a net outward force on the arc [as shown in Fig. 1(b)] which enhances the arc displacement and drives the instability. The instability is stabilized by increased heat losses near the wall and increased heating near the arc center, which limit the excursion of the arc channel from the center of the discharge. Narrowing of the arc channel in metal halide lamps, as compared to arc discharges where most power is transported out by thermal diffusion, is a direct consequence of the high-power efficiency of the lamp.7 Unfortunately, a decreased arc diameter gives the arc more space and increases the chance of current inhomogeneities, causing the helical instability. This is consistent with the experimental observation that instabilities often start in a region of increased arc constriction. The previously developed theory of the helical arc instabilities1–3 is only partially applicable to metal halide lamps for various

FIG. 1. Left: A drawing of a metal halide lamp. The arc discharge is operated inside the polycrystalline alumina burner (2) with two tungsten electrodes. The burner is placed inside an evacuated outer glass tube. A getter (1) is used to eliminate impurities and maintain good vacuum. Right: A schematic drawing of the magnetically induced instability in the arc plasma. The arc current J, is surrounded by a circular magnetic field. This results in a symmetric confining force on the arc. A disturbance resulting in a non-uniform current profile creates a net outward force on the side of the highest current, which starts the arc instabilities.

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reasons: The spatial segregation is severe and the gas mixture is strongly nonuniform, in particular for vertical operation. Furthermore, wall and electrode effects are always important and the lamps are ac operated. Moreover, convection, which is not included in the existing theories, seems to strongly affect the instability in the lamps. In order to gain a better understanding of the onset and behavior of instabilities as well as the influence of convection an experimental study at varying gravity conditions has been performed.

The experiments have been performed in an airplane during parabolic flights. In these flights, a level flying airplane pulls up strongly before reducing the engines significantly and going into a parabolic free fall for about 20 s. At the end off the parabola, a second strong acceleration is used to prevent the plane from crashing. The result is that the experiment is subjected to a series of $1g - 1.8g - 0g - 1.8g - 1g$ gravity conditions. During the hypergravity phases, there is an increased convection, whereas there is virtually no convection during the microgravity phase. Since no stable lamp operation can be achieved in the 20 s of microgravity in the plane, additional experiments have been performed in the International Space Station (ISS).

Special metal halide lamps with a CeI$_3$ filling have been designed for these experiments. The 0.8 mm thick cylindrical burner of polycrystalline alumina has a 4.9 mm inner diameter and 14.5 mm inside length. Tungsten electrodes end 1 mm inside the burner, which is filled with 6 mg CeI$_3$ and a varying amount of Hg. 200 mbar Ar is added as a starting gas. The burner is placed inside a double-ended vacuum quartz outer bulb [cf. Fig. 1(a)]. A metal wire—not shown in Fig. 1—is wound around the burner for safety reasons. The lamps are operated using a modified Philips Dynavision electronic ballast supplying a 85 Hz square wave voltage at an adjustable and controlled power level between 40 and 150 W, which is controlled using the DALI bus protocol. The lamps are observed side-on using a web cam. Note that this implies that no arc displacements toward or away from the web cam can be observed. Consequently, only the projection of the displacements on the focal plane is monitored and the true helical nature of the instability cannot be verified. Due to the nature of the translucent polycrystalline alumina burner, no sharp images of the arc can be obtained. Arc displacement and instabilities, however, can be easily seen, as shown in the two web cam images of Fig. 2. The first image shows a fully developed instability under normal gravity conditions. The instability (observed as a projection as explained above) appears as a full period standing wave with fixed end points at the electrodes; the two opposite maxima periodically changing sign. This suggests that the instability consists of one full helical turn rotating around its axis. The second picture [Fig. 2(b)] shows the instability under microgravity. In this case, only a single curve in one direction is observed, suggesting a straight rather than helixlike structure. Moreover under microgravity conditions, in all but one case the arc position was stable, even during the extended observation times of a several minutes in the space station. This suggests that convection is the driving force behind the arc rotation.

Figure 3 shows that the displacement of the center of the arc increases as a function of lamp power and current under microgravity conditions. These measurements were taken in the ISS for two different lamps with identical fillings, whose deviations both seem to be mainly in the field of view. It shows that the instability is quite reproducible and driven by the self-induced magnetic field. As the magnetic field depends on the lamp current, a threshold current for the onset of the instability is expected. Furthermore, the deviation increases with increasing current; showing the combined effects of an increased magnetic force and a hitherto not fully understood counterforce, which obviously has a less strong dependence on the arc current.

Measurements during parabolic flights have shown that the threshold current at the onset of the instability is reduced as gravity increases, which indicates that convective flows somehow enhance the instability. This is also visible in Fig. 4, where the rotation frequency of the instability is shown for two lamp pressures at normal and hypergravity as a function of lamp power. It appears that the lamp pressure has little influence on the rotation frequency, whereas the frequency decreases with increasing lamp power. Furthermore, the rotation frequency is systematically higher in case of hypergravity as compared to normal gravity.

From the above experiments, it is obvious that helical instabilities occur readily in metal halide discharge lamps. They often start in regions of arc constriction above a thresh-

![FIG. 2. Images of the helical instability in a metal halide lamp. Left: Metal halide lamp at normal gravity conditions. A rotating double helixlike structure is observed. Right: A metal halide lamp (6.63 mg Hg; 25 bar) under zero gravity, where typically a single nonrotating arc is observed. The horizontal black lines are the images of the safety wire around the burner [not shown in Fig. 1(a)].](image)

![FIG. 3. The displacement of the arc center from the burner axis as a function of lamp power at microgravity conditions [cf. Fig. 2(b)] for two lamps (full squares and diamonds) both filled with 3.98 mg Hg (15 bar) and 6 mg CeI$_3$. The lamp current is plotted on the right axis (open squares and diamonds).](image)
old lamp power and current. The self-induced magnetic field from the lamp current is driving the helical shape of the instability, which starts to rotate due to the convective flows in the lamp (i.e., the helical structure moves upward driven by convection, which leads to an apparent rotation). The rotation of the helical instability is fully dependent on convection and absent at microgravity conditions. In the latter case, only a stationary curved arc has been observed. The results presented here can be used to verify existing and forthcoming theories on the onset, development, and general behavior of the helical instability in metal halide lamps.

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