Fast Track Communications

IOP Publishing Plasma Sources Science and Technology

Plasma Sources Sci. Technol. **24** (2015) 022002 (6pp) doi:10.1088/0963-0252/24/2/022002

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Gravity effects on a gliding arc in four noble gases: from normal to hypergravity

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Received 20 October 2014, revised 3 February 2015
Accepted for publication 20 February 2015
Published 19 March 2015

Abstract

A gliding arc in four noble gases (He, Ne, Ar, Kr) has been studied under previously unexplored conditions of varying artificial gravity, from normal 1 *g* gravity up to 18 *g* hypergravity. Significant differences, mainly the visual thickness of the plasma channel, its maximum elongation and general sensitivity to hypergravity conditions, were observed between the discharges in individual gases, resulting from their different atomic weights and related quantities, such as heat conductivity or ionisation potential. Generally, an increase of the artificial gravity level leads to a faster plasma channel movement thanks to stronger buoyant force and a decrease of maximum height reached by the channel due to more intense losses of heat and reactive species. In relation to this, an increase in current and a decrease in absorbed power was observed.

Keywords: gliding arc, noble gases, hypergravity

(Some figures may appear in colour only in the online journal)

Since plasma science mostly deals with charged particles, the gravitation force, which is much weaker than the electromagnetic force, is often neglected. Although this might be just and reasonable for many kinds of discharges, there are cases where gravity plays a crucial role through its action on neutral particles. Typical examples include astrophysical plasmas, dusty plasmas, arcs, plasma torches and others.

In these discharges the alteration of real or apparent gravity (*g*-force) could significantly change the plasma properties with consequences for both fundamental and applied science. Study of the electric discharges in altered gravity could be important for electrical and fire safety precautions at high accelerations (space flight, aircraft, racing), ion thruster design, or understanding the plasma related processes in the atmospheres of other planets, where the gravity is significantly stronger or weaker than that on Earth. One of the discharges where the gravity has to be taken into account is a gliding arc.

A gliding arc is similar to well known stable arc discharge [1]. It differs in the electrodes geometry, which in the case of a gliding arc enables the vertical movement of the plasma channel. This movement is caused by: (i) gravity-dependent buoyant force originating from the temperature difference between the hot plasma channel and cold surrounding atmosphere and/or (ii) the drag of gas, which typically comes from below. In a standard gliding arc configuration with divergent electrodes, the length of the discharge channel increases as the arc is moving upwards. When the length exceeds a critical value, the discharge extinguishes and a new one is ignited at the minimum distance between the electrodes at the same moment [2]. This repetitive character of a gliding arc lifecycle with a characteristic time period is one of its most distinguishing attributes. At low current density, i.e. in a so-called glowing arc [3] mode, gliding arc properties are similar [2] to non-equilibrium atmospheric pressure glow discharges.

The gliding arc has been studied intensively from the point of view of fundamental research [4–6], as well as an outstanding plasma source for various industrial applications [7, 8]. The gliding arc is usually studied in a flow regime with a relatively high flow rate, which governs the discharge dynamics, especially the vertical speed of the plasma column [5, 9, 10]. In such a case, the buoyancy plays only a minor role and the gas drag dominates. So to study the buoyancy effects, the gravity level should be increased to emphasise the buoyancy compared to the gas flow effects. Several experiments have been performed to explore the gravity effects on standard arc discharges [11–13]. Only recently have the first studies [6, 14, 15] about the influence of increased gravity on the gliding arc behaviour been published. In higher gravity levels the plasma channel glided faster and the whole life cycle was shorter. Here, an extension and improvement to our previous papers is made by carrying out the experiments in four noble gases—He, Ne, Ar and Kr. These were chosen both for their similarities (they are all monoatomic and non-reactive gases) as well as for their differences (their atomic masses cover a wide range, which results in a wide spread of dependent quantities, e.g. thermal conductivity).

The experiments in hypergravity (up to 18 *g*) were performed by using the Large Diameter Centrifuge (LDC) at ESA-ESTEC centre in Noordwijk, the Netherlands [16]. The whole experimental setup (except the spectrometer) was placed inside the centrifuge gondola. Given that the detailed description of the experimental apparatus and methods has been presented in [14], only a brief overview follows.

The discharge at atmospheric pressure was operated between slanted copper electrodes with a minimum distance of 4.5 mm and an initial angle of 36° between them. The electrodes were enclosed in a non-conductive discharge chamber with 2 litre inner volume with holes for gas inlet and outlet. The discharge voltage was supplied via a variable autotransformer (0–250 V, 50 Hz AC) by high voltage transformer (0–10 kV). Three multimeters were used to measure the RMS voltage, current and power on the primary winding of the high voltage transformer. A high voltage probe and a Rogowski coil current probe were used to measure the instantaneous electric parameters of the discharge. The discharge visual appearance was recorded as a video (up to 1000 frames/s) and as standard photographs by a digital camera.

Although the experimental device is essentially the same as in [14], the sealing of the discharge chamber was improved and the longer exhaust tube suppressed possible air backstreaming. Altogether, these changes significantly improved the purity of noble gas inside the discharge chamber. The amount of air admixtures in the noble gas was estimated from spectroscopic measurement to be in the order of 0.1% or better.

The main features of the gliding arc appearance will now be discussed based on figure 1, where long exposure (0.1–1 s) photographs of the gliding arcs at various conditions in He, Ne, Ar and Kr are shown. Each row corresponds to one gas and each column to different experimental conditions. The photographs in columns 1–4 were taken remotely from inside the centrifuge gondola and they show the changes that the gliding arc in each gas undergoes with the increase of artificial gravity. The experimental conditions were deliberately set differently for each gas to enable gliding of the plasma channel already in 1 *g* conditions and simultaneously not to mask the gravity effects by too high a gas flow. Unfortunately, due to severe complications (including the influence of hypergravity on the camera lenses, shallow depth-of-field, impossibility to remotely control the camera during experimental runs at LDC), the quality of some of the photographs was affected. The rightmost column shows the photographs taken in laboratory 1 *g* conditions with gas flow increased by 1 slm compared to the columns 1–4 for each gas. The changes in brightness between the images are not to be attributed to plasma processes but to different exposure times. In the majority of the photographs (except for Ar and Kr, both at 1 *g* and 2 *g*), rather long exposure time and high gliding frequency caused an overlaying of many glides of the plasma channel.

The most pronounced differences among gases in the first column of figure 1 are: apparent colour of the gliding arc plasma, which is naturally determined by dominant spectral lines of each gas, the thickness of the plasma channel and its maximum elongation.

The thickness of the plasma channel was observed to be visually wider for lighter gases (helium and neon) and thinner for heavier gases (argon and krypton). The phenomenon of radial contraction can be attributed to the inhomogeneous heating in the radial direction due to finite thermal conductivity of the gases, which is more than 20 times lower for krypton than for helium at 300 K and this difference increases even more at higher temperatures [17]. As a result, the gliding arc in helium and neon had a rather diffusive character, while in argon and krypton the sharp edges of individual filaments could be distinguished [15]. Unfortunately, quantitative analysis of the filament thickness is difficult: for the long exposure photographs in figure 1, the unceasing movement of the plasma channel causes motion blur of several millimeters and the low resolution of our high speed camera leads to comparably high uncertainty.

The maximal elongation of the plasma channel before extinguishing was also different for each gas. Generally, the gliding arc in krypton was able to rise much higher than the gliding arc in lighter gases. In typical conditions (low *g*-level, the gas flow low enough to maintain regularly shaped individual plasma channels) the gliding arc in krypton and argon was even able to easily ascend above the electrodes—meaning that the end points of plasma channels reached the top of electrodes, yet the centre of the arc continued to rise up (see images in [15]). This can probably be attributed to the lower

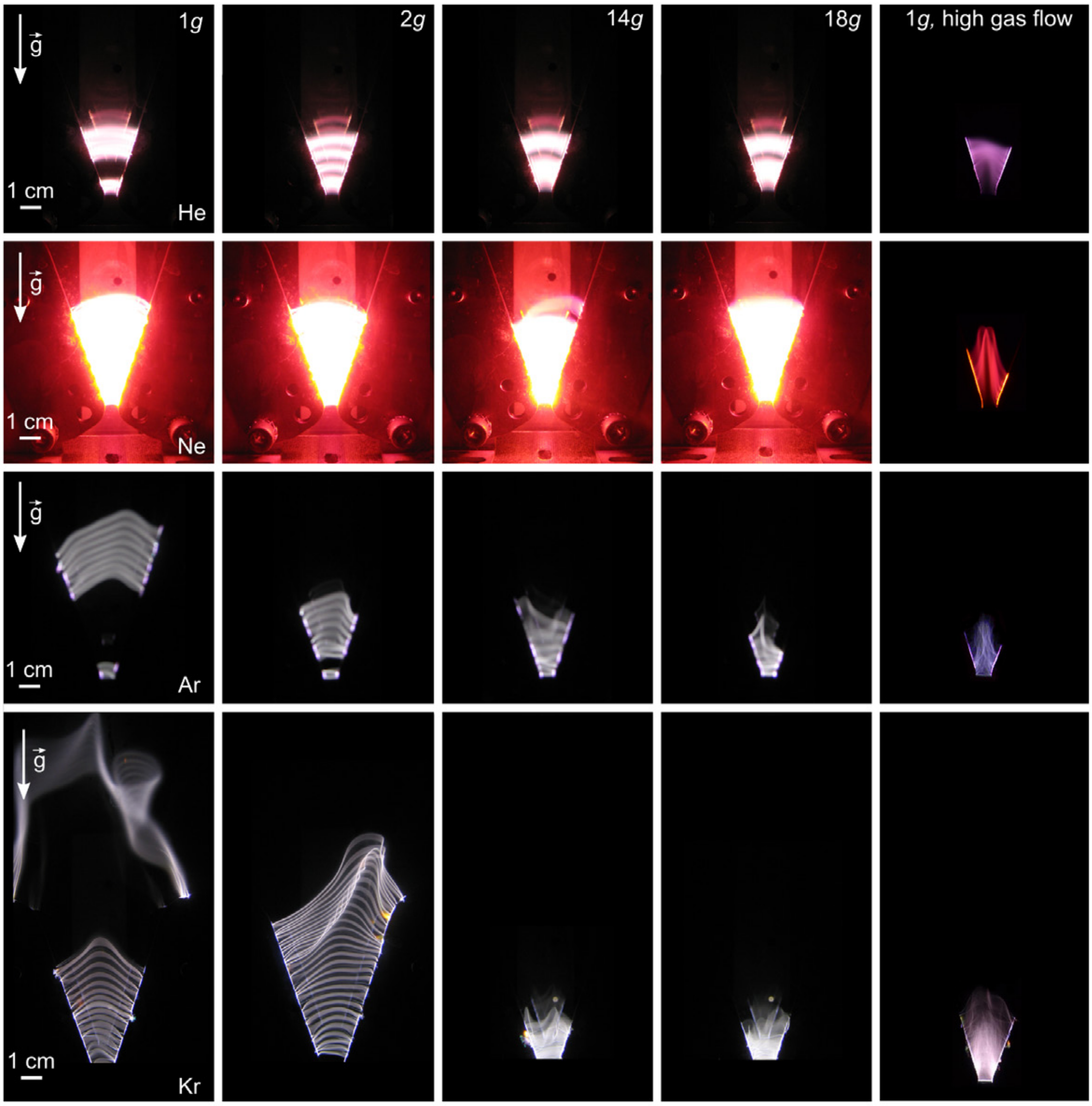

Figure 1. Long exposure photographs of the gliding arc in helium, neon, argon and krypton. Experimental conditions for each of the columns 1–4 (dependence on artificial gravity level) were set to enable gliding of the arc already in 1 *g*: helium—1.37 slm, 8 kV; neon, argon and krypton—0.4 slm, 4 kV. Conditions in column 5 differ in the gas flow, which was increased by 1 slm for each gas. Exposure times of photographs in columns 1–4 were: He—0.1 s, Ne—1 s, Ar—0.1 s, Kr—0.3 s; exposure times of photographs in column 5 were: He—0.1 s, Ne—0.1 s, Ar—0.1 s, Kr—1 s.

ionisation potential of heavier gases, which makes sustaining the discharge easier than in helium or neon.

The influence of increasing hypergravity can be observed on photographs in columns 2–4 of figure 1. With the increase of gravity, the gravity-dependent buoyant force acting on the plasma channel gets stronger, making its upward movement faster. However, due to faster convective cooling, the losses of excited atoms and heat become more intense and cause the decrease in maximum height. This decrease is the most significant for krypton and the least significant for helium. This different sensitivity of each gas to an increase in gravity is the result of various factors, one of them being the gas atomic weight. The resulting gravity-dependent force (the difference between downward gravitational force and upward buoyant force) acting on the heated arc channel is proportionally dependent to the mass density difference between a cold and a heated noble gas. This difference is proportional to the atomic weight of the gas (4, 20, 40 and 84 for He, Ne, Ar and Kr) and so the hypergravity effects are much more profound for krypton than for lighter gases. Also, the thin filament of krypton transfers the heat to the colder environment more slowly than the wide diffusive helium plasma channel. This effect is intensified by the fact that helium is a good heat conductor compared to krypton. Thus, the temperature difference between the heated and cold gas is bigger for heavier noble gases, therefore enhancing the hypergravity effects. Finally, the thinner the plasma filament, the less gas aerodynamic resistance it has to overcome during its upward movement.

In the gliding arc device with the gas feed from below, the plasma channel is lifted up by a combination of two forces: buoyant force and gas drag. Increasing either of them will make the resulting upward force acting on the

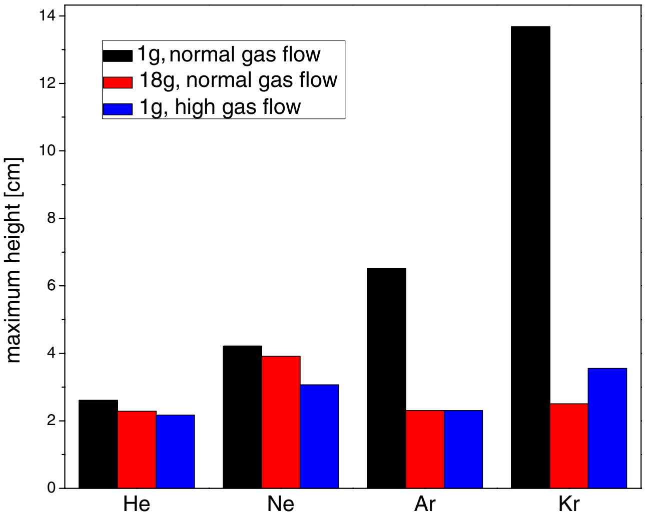

Figure 2. The maximum heights of gliding arcs calculated from image analysis of figure 1 in 1 *g*, 18 *g* and high gas flow conditions.

plasma channel become stronger. Which component of the force will dominate depends on the *g*-level and on the gas flow rate. The high gravity case was already discussed and the high-flow case (approximately 1 slm above the normal flow conditions presented in columns 1–4 of figure 1: helium—1.37 slm → 2.37 slm; neon, argon and krypton—0.4 slm → 1.4 slm) is presented in column 5 of figure 1. The high gas flow influences the motional characteristics of the gliding arc as the plasma channel is dragged by the fast moving gas. It was found that even though this force is of a different nature to the buoyant force the main effect on the gliding arc remains the same—the speed of the plasma channel increases, convective cooling also increases and as a consequence the maximum height of the arc decreases and new ignitions occur more frequently.

The recapitulation of maximum heights in four gases in 1 *g* versus 18 *g* versus high gas flow from figure 1 can be seen in figure 2. As discussed above, the increase of the artificial gravity level did not cause similar changes in all four gases. The decrease of maximum height in helium and neon is only small (around 10%), while in argon and krypton the decrease is significant (over 50%). Krypton is the only gas in this experiment, for which the increase of artificial gravity caused a bigger decrease of the maximum height than did the increase of the gas flow.

In the above-described experiment, the experimental conditions for individual gases differed in order to maintain the gliding motion of the plasma channel. If the conditions were set the same for each gas, then the situation might be drastically changed, as will be shown in figure 3. Here, the gas flow rate was 0.15 slm for each gas and the discharge voltage, 4 kV, was also the same for each gas. Besides the maximum height, the frequency of new ignitions (or gliding frequency) (figure 3(*a*)) is also a valuable parameter for the study of hypergravity influence because it effectively combines both the maximum height reached by the plasma channel (figure 3(*b*)) and the velocity of its movement (figure 3(*c*)). For these particular experimental conditions, the lightest of the gases—helium—appeared in the form of stable arc-like plasma channel for all *g* conditions (zero gliding frequency) because the upward force was not strong enough to lift the arc up. The second lightest gas—neon—also started as a stable plasma channel but was able to undergo a transformation to a gliding arc after an increase of the artificial gravity level above 8 *g*. The buoyant force for the discharge in argon and krypton was strong enough to initiate gliding already at 1 *g*, although the frequency was quite low, since the plasma channel moved rather slowly and quenched (and reignited) after travelling a relatively long distance. With increasing gravity, the gliding frequency increased to values many times higher for all three gases for which the discharge appeared in the form of a gliding arc. However, one must keep in mind that the gliding frequency is a time-averaged quantity, so it exhibits a statistic behaviour and, hence, the individual glides may differ a lot. Moreover, the gliding arc is also influenced by the system history (e.g. preheated electrodes, gas circulation) and shows signs of hysteresis. We repetitively observed that the transition from stationary into gliding mode happens at a higher gas flow rate than reverse transition (from gliding into stationary mode), probably thanks to the positive feedback between the ambient gas circulation and plasma channel gliding.

The electrical parameters that were directly measured on the primary winding of high voltage transformer are plotted in figure 3(*d*). Since the discharge in helium was not in a form of a gliding arc but a stationary arc-like discharge, it is not included in the graphs, the same goes for neon in *g*-levels below 8 *g*. The curves for neon and argon are almost constant, while for krypton they exhibit a clear dependence.

In krypton, as the *g*-level increases, the power input into the primary winding (see figure 3(*d*) solid symbols) decreases as a consequence of the lowered power consumption in the gravity-shortened plasma channel [2]. Simultaneously, the primary winding current increases (see figure 3(*d*) open symbols), albeit slightly. This counter-intuitive behaviour is most probably caused by the non-ideality of the transformer, i.e. its transformation matrix is not diagonal, it is complex and may even be non-linear. The substantial primary current error bars at low *g*-levels would then be a consequence of the sensitivity of the current to the phase variations for a given voltage and power at low power factors.

The plots of primary current and RMS power for neon and argon are almost constant with *g*-level because their height decreased insignificantly.

In this paper, we have shown that the increased artificial gravity (up to 18 *g*) spectacularly influences the properties of the gliding arc discharge between diverging electrodes. Four noble gases of atomic weight in wide range (He, Ne, Ar and Kr) were used to reveal how the differences in gliding arcs observable at 1 *g* affected their peculiar behaviour at higher *g* levels.

At the elementary level of the complex interplay of physical phenomena evoked by hypergravity, there is an increase of the gravity-dependent buoyant force. The stronger buoyancy initiates faster movement of the plasma channel, which

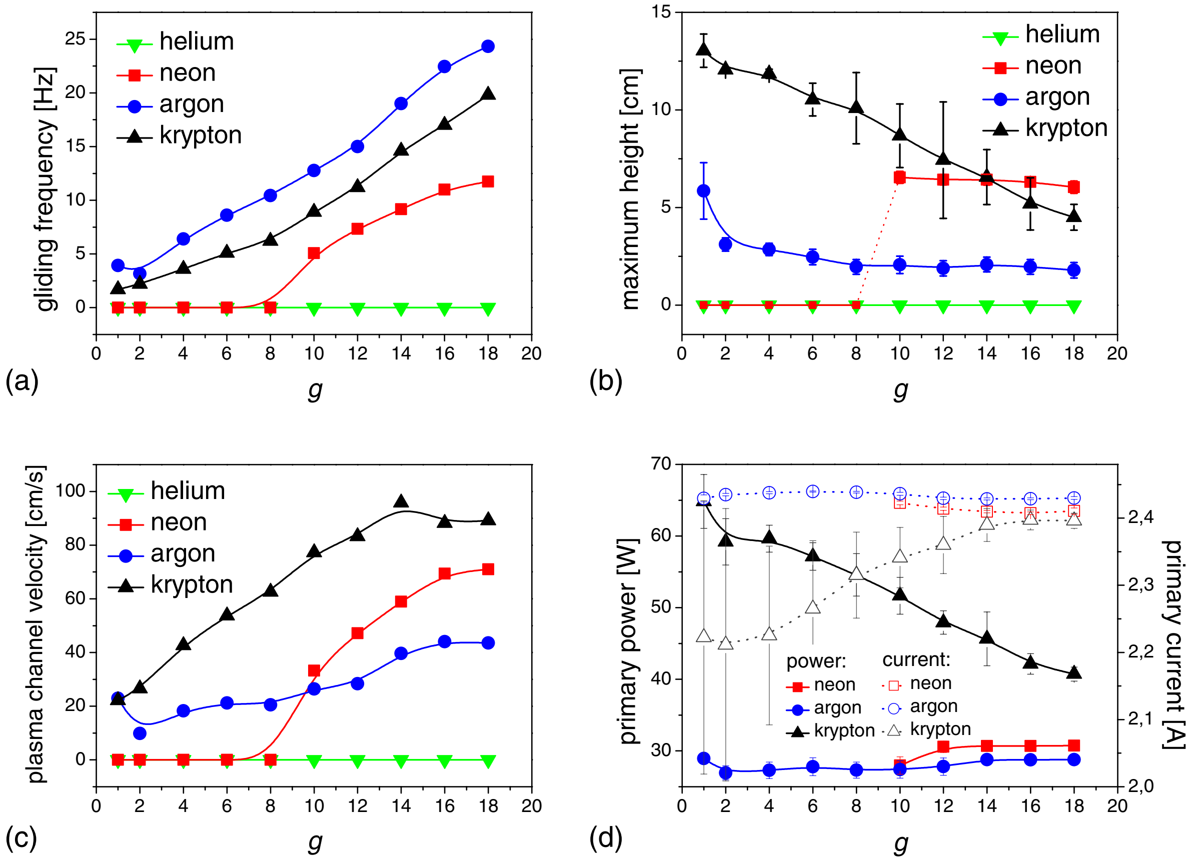

Figure 3. (*a*) The gliding frequency, (*b*) maximum height reached, (*c*) velocity of the plasma channel and (*d*) primary winding power and primary winding current of the gliding arc in He, Ne, Ar and Kr at low gas flow (150 sccm) and 4 kV discharge voltage, as a function of the gravity level.

increases the losses of excited species and heat and thus results in the decrease in maximum height reachable by the plasma channel. These changes of the plasma properties are then reflected in the electrical parameters of the discharge. All of these effects of the varying gravity on the gliding arc discharge are strongly interconnected and create a complex system that is very sensitive to all of the experimental conditions, even with signs of hysteresis behaviour.

Acknowledgments

This work was supported by European Space Agency SpinYourThesis! 2013 programme, Masaryk University Rector's Scholarship, project CZ.1.05/2.1.00/03.0086 funded by European Regional Development Fund and project LO1411 (NPU I) funded by Ministry of Education Youth and Sports of Czech Republic. We would also like to thank Mr A Dowson from ESA-TEC-MMG for his support of these studies.

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