

Characterization and Applications of Non-Magnetic Rotating Gliding Arc Reactors ~ A Brief Review

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ABSTRACT: Gliding arc discharge (GAD) reactors are known for high energy efficiency and good chemical selectivity compared to non-thermal plasmas such as glow discharge, corona and dielectric barrier discharge. Reported literature identified that planar diverging GAD have non-uniform gas treatment (e.g. only 20% of gas processed by plasma depending on electrode configuration). Further requirement of minimum limit gas velocity to drag the arc results in lower gas residence time.

This paper attempts to investigate the GAD performance and preliminary studies to overcome some of the identified drawbacks, by using only fluid mechanics without magnetic field (rotating gliding arc (RGA)) inside the plasma reactor developed in various research laboratories. This article discusses the applications of GAD and also focuses on bringing out the performance and comparing with the results from the existing non-magnetic rotating gliding arc reactors. The paper also summarizes results from literature in such reactor designs.

Keywords: Perovskite, Ultrasonic velocity, Grain size, Curie temperature

1. Introduction

Plasmas can be classified into thermal and non-thermal plasmas. Thermal plasmas are mainly used in applications involving enormous heat or temperature and they enhance overall product value [1]. In recent times, non-thermal plasma is extensively used in applications involving low temperature chemical reformations which are not favoured by thermodynamic chemistry [1,2]. However, non-thermal plasmas such as glow discharge, corona & silent discharge and dielectric barrier discharge (DBD) show limitations in terms of power and operating pressures [3,4]. These disadvantages are overcome by gliding arc discharges (GAD) which have very high electron density compared to DBD and corona [5–7] thereby improving energy efficiency [5,8]. Energy efficiency indicates the efficiency of the plasma process based on energy spent on plasma chemical process, compared to the standard reaction enthalpy for the same process as shown in Equations 1, 2 & 3 [9].

Effective conversion of reactant 'i'

$$= \frac{\text{difference in molar flow rate at inlet and outlet of 'i'}}{\sum_i \text{molar flow rate of 'i' at inlet}} \quad (1)$$

$$\text{Total conversion} = \sum_i \text{Effective conversion of reactant 'i'} \quad (2)$$

Energy efficiency=

$$\text{Total conversion} \times \frac{\Delta H_{298}^{\circ} \left(\frac{\text{kJ}}{\text{mol}} \right)}{\text{Plasma power input} \left(\frac{\text{kJ}}{\text{mol}} \right)} \quad (3)$$

In traditional planar diverging GAD, high gas flow rate is preferred to enable the arc gliding. Also, the plasma zone is confined to the flat region between the electrodes. Due to these reasons, only fraction of gas is processed which is only 20% as reported in [10]. This leads to drop in amount of gas processed for a unit of plasma power spent and also reduces degree of chemical selectivity [3].

In order to overcome these drawbacks, a rotating gliding arc (RGA) reactor without magnetic field [11–19] is developed in various research laboratories. Characterization of RGA include determining electrical characteristic such as operational voltage, current & power [11–19], plasma parameters such as species temperature, species density & electron energy distribution function [19], arc dynamics including arc length, arc diameter & arc rotational frequency [20], operational characteristics such as flow rate, reactor geometry [11–19] and influence of one characteristics on the other [11–19] to optimise or tune the performance of the built reactor. In this paper we provide a brief review of gliding arc reactors and highlight the design and characterisation works of the existing non-magnetic rotational gliding arc reactors.

1. Traditional Gliding Arc Reactor

The gliding arc has been known for more than one hundred years in the form of Jacob’s ladder [1]. GAD is an auto-oscillating periodic phenomenon between at least two diverging electrodes positioned in a laminar or turbulent gas flow as shown in Fig 1 [1]. It is self-initiated, at the narrowest gap and the discharge forms the plasma column connecting the electrodes. This column is dragged by the gas flow towards the diverging downstream section. The discharge length grows with the increase of inter-electrode distance until it reaches a critical value, usually determined by the power supply limits. After this point the discharge extinguishes itself only momentarily to reignite itself at the minimum distance between the electrodes and a new cycle starts. The time-space evolution of the gliding arc is illustrated by a series of snap-shots shown in Fig 1 [1].

One unique feature of the gliding arc is that, it is in thermal equilibrium during its breakdown and shifts to non-equilibrium mode as it glides along the electrode. Gliding Arc Discharge (GAD) is powerful non-thermal plasma system with elevated gas temperatures that can be considered as intermediate “warm” plasmas [21]. Most recent “warm” discharges are based on the gliding arc, which has gas temperatures in the range of 2000-4000 K [21]. Power and temperature of GAD are high enough for intensive chemical conversions and radical production, while the energy losses can be minimal. Thus, energy costs can be quite low with GAD reactors [22]. However, non-uniform gas distribution i.e., channelling of the gas in the GAD escaping the plasma zone, low gas residence time and low plasma volume are some of the major drawbacks mainly associated due to the planar electrode configuration [21].

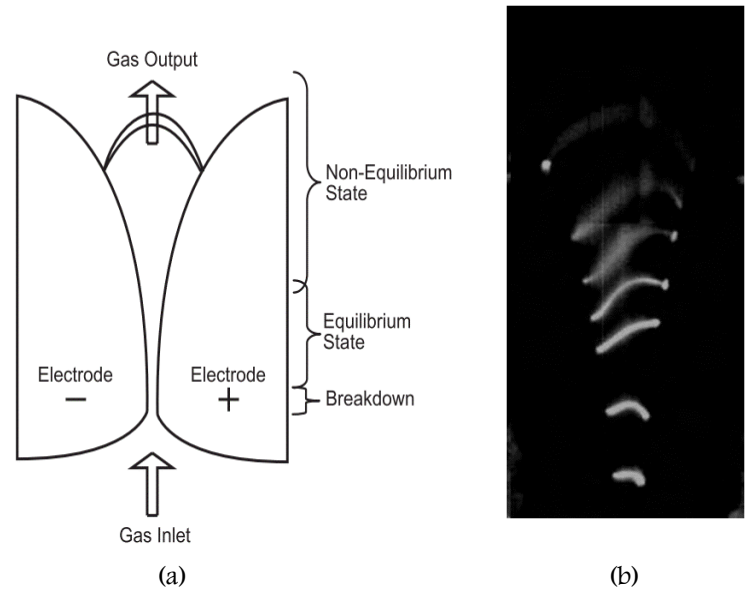


Fig 1. Gliding Arc Discharge (a) Transition phases (b) Snapshot of Gliding Arc Evolution [1]

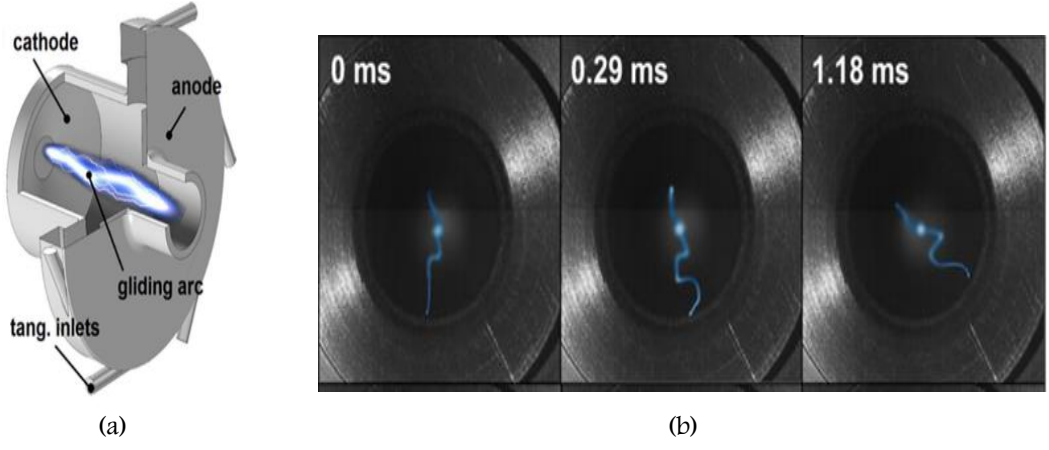


Fig 2 a) Schematic representation of rotating gliding arc, b) Snapshots of arc rotations at different time interval [18]

3 Rotating Gliding Arc Reactor

3.1 Introduction

To address the limitations of the traditional GAD design, researchers have evolved a series of new designs which does not use the planar electrode geometry. Once such design is a rotating gliding arc reactor (RGA) as shown in Fig 2 [18]. The name rotating gliding arc has thrived as the arc is made to rotate while it's glided between two electrodes. This rotational feature opens various possibilities of electrode configurations to enable the arc rotation and thus increasing the plasma volume [23]. The rotation is mainly achieved either by the influence of tangential velocity component of gas flow or using external magnetic field either by permanent magnets or electro magnets [4,24–26] . However, inclusion of magnetic field implies additional energy consumption, scalability issues and confinement of arc rotation to a plane [18].

3.2 Characterization of Non-Magnetic Rotational Gliding Arc Reactors

Table 1 summaries the electrode configurations available in non-magnetic RGA and the performance parameters from the literature.

The gas rotation is predominantly achieved using gas vortex. Researchers have used several configurations by varying the electrode arrangement; changing the shape and role of the two electrodes i.e., high voltage (HV) electrode and the ground electrode. Various electrode shapes including cone shaped solids [11], spiral [12, 16], reactor wall, ring [12, 16], helical [17] and rod-shaped designs [13] have been studied to achieve rotational gliding arcs.

Fig 3-(a) shows cone shaped high voltage electrode with the cylindrical reactor body as ground electrode. In this work, researchers have conducted experiments with methane and air as the plasma forming gas and the studied gas flow rates are in the range of 10-20 LPM as shown in table 1. As shown in Fig 3a, in this design, one end of the arc is attached to tip of HV electrode whereas the other end is either at wall of reactor body or at the edge of the reactor body depending on the power supply chosen. Though this design allows to achieve rotation of the arc, unless the length of the arc is elongated to the maximum by operating at higher powers, the volume of plasma formed will be less in this design. The other limitation of this design is the the reactor body is electrically live requiring additional safety measures.

Table 1. Non-Magnetic Rotating Gliding Arc Reactors' electrode configuration and characterisation work

Plasma Reactor Type	HV electrode	Ground electrode	Power supply	Feed	Flow Rate (LPM)	Characteristics	Ref.	Ref.
Rotating Gliding Arc (RGA)	Cone shaped solid	Hollow cylinder	AC, 10kHz	CH ₄ , Air	10-20	Voltage-current probe (VI-p), onochromator-detector	[11]	Error! Reference source not found.- (a)
Gliding Arc Tornado (GAT)	Spiral	Circular ring	DC	Air	<12	VI-p, Camera	[12]	Error! Reference source not found.- (b)
Gliding Arc Discharge in laval nozzle	Laval nozzle	Cylindrical rod	AC, 50Hz	N ₂ , O ₂ , Air	16-66	VI-p, High speed Camera (HSC)	[13]	Error! Reference source not found.- (c)
Reverse vortex Gliding Arc	Circular disc	Rod with SMAE	AC, 5kHz	Air	Re = 1174 to 2609	VI-p, HSC	[14]	Error! Reference source not found.- (d)
RGA	Cylindrical rod	Hollow cylinder	AC, 50Hz	Air	2	VI-p, ICCD	[15]	Error! Reference source not found.- (e)
Vortex Gliding Arc Plasma (VGAP)	Spiral	Circular ring	DC	Air	11	HSC	[16]	Error! Reference source not

								found.- (b)
GAT	Helical	Vortex chamber	AC, 60Hz	Air, Natural gas	12, 36	V probe	[17]	Error! Reference source not found.- (b)
Gliding Arc Plasmatron (GAP)	Portion of the reactor	Feed Outlet	DC	CO ₂	10-22	HSC	[18]	Error! Reference source not found.- (f)
VGAP	Cylindrical rod	Hollow cylinder	AC, 50Hz	Humid air	2	VI-p, ICCD, OES	[19]	Error! Reference source not found.- (e)

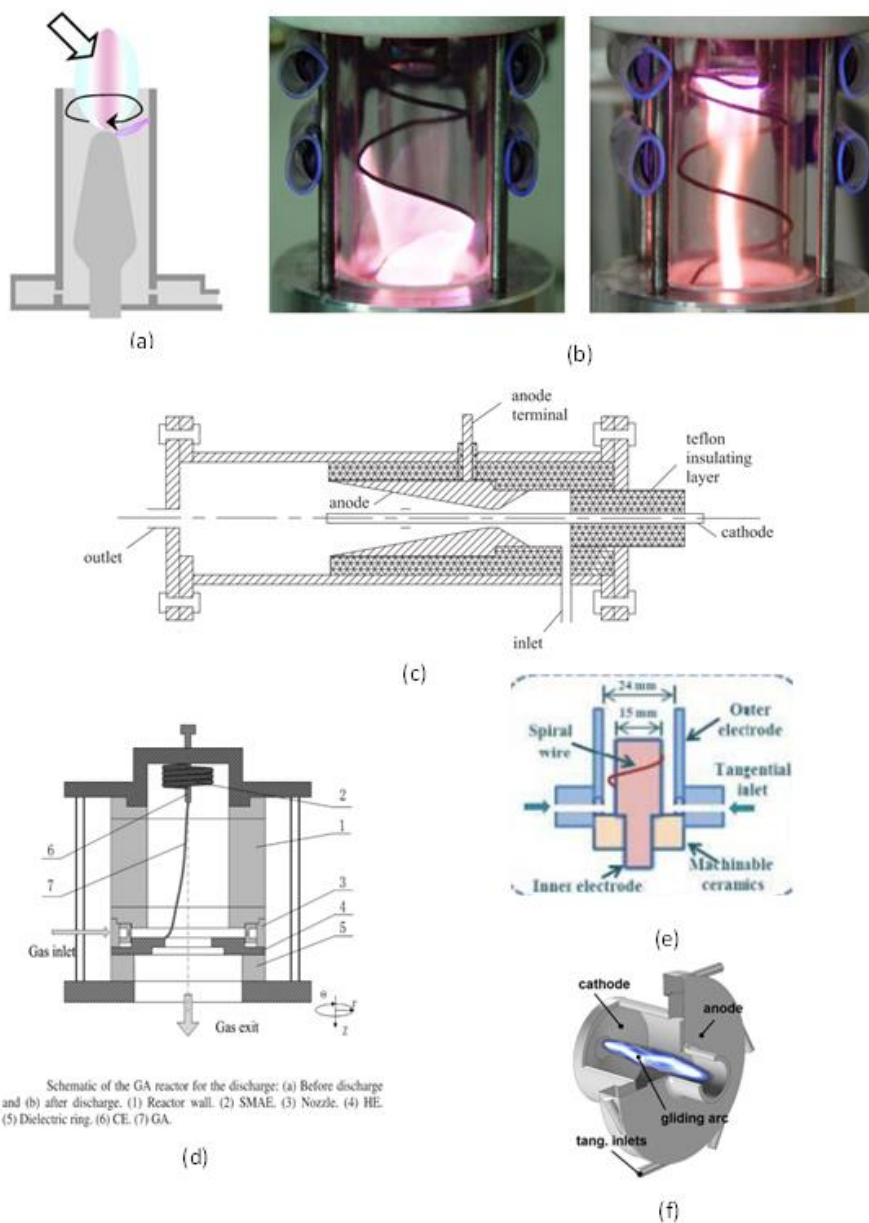


Fig 3. Rotating GAD designs in literature

Fig 3-(b) shows a spiral electrode design with annular ring as ground electrode. The electrodes are enclosed in a glass or quartz reactor. In this design, the arc is ignited at the shortest gap and is forced to follow the spiral path. As the arc elongates, the arc attaches to the bottom, provided the power applied is sufficient enough to sustain operations. The main drawbacks of this design include (i) the pitch of spiral should match the pitch of the gas flow to achieve stable operations; (ii) the spiral design creates more hindrance to the path of gas flow and effects arc rotation negatively, (iii) this design is difficult to scale; and (iv) requires higher power to sustain operations. As shown in table 1, most of the reported works in the literature, resembles this configuration with minor modifications.

Fig 3-(c) shows a conical diverging electrode design with central rod as second electrode, incorporating laval nozzle. Researchers have shown that using oxygen, Nitrogen or air flow they have been able to achieve a turn down ratio of about 4 with the flow rate ranging from 16 to 64 LPM. The electrode configuration used in Fig 3-(d) is similar to Fig 3-(b) incorporating spiral electrode made of shape memory alloy (SMA). The SMA electrode (SMAE) deforms at fixed low and high temperature, thus remembering two typical shapes. The arc which is in thermal mode during the ignition heats up the SMAE, thereby allowing it to contract and elongate the arc. The arc detaches from SAME and connects to the central rod upon maximum elongation of the arc. SMAE deforms again once it is cooled to lower temperature. This eliminates the spiral electrode being an obstacle to the gas flow during the process. However, the quenching of arc by gas flow is different at different flow rates upon scaling up. This might require the need for designing SAME of different set temperatures for deformation. Hence, this configuration is susceptible for extensive arc quenching.

The design shown in Fig 3-(e) is similar to the one shown Fig 3-(a) and the maximum flow rate used in this study was only 2 LPM. This could be due to the less flow zone gap between two electrodes which is 9mm. In the design shown in Fig 3-(f), researchers have worked with certain distinction from other designs by incorporating the reactor body or components itself as the electrodes separated by an insulation. The reactor is tested extensively using CO₂ as the plasma forming medium and flow rate up to 22 LPM is studied. This design uses the reactor body itself as electrodes. The main disadvantage of this design is that the entire reactor should be scaled up for larger plasma volume which might also require additional power to sustain, leaving no option to control the arc volume only by varying electrode configuration as the reactor body plays the role of the electrode.

3.3 Applications of Gliding Arcs discharge reactors

Gliding arc reactor is most suitable for applications such as pollution control to remove residual unwanted species, fuel conversion, dissociation of CO₂ and H₂S, H₂

generation from CH₄, water-gas shift reaction and removal of tar compounds from syngas. GAD could generate high density of reactive species such as electrons, radicals, ions, excited species. Based on the nature of feed, the generated species drive the chemical processes even at ambient gas temperature. The presence of thermal arc regime for a very short duration at breakdown is also acts as an added advantage to use GAD. GADs are widely researched to address broad spectrum of applications. GAD operates in the range of few 100's of watts to a few kW, to achieve higher reactor productivity and also high degree of non-equilibrium plasma for chemical selectivity. Table 2 shows some of the applications where gliding arc is used.

One of the most researched application of GA is the dry reforming of methane. Dry reforming of methane [27,28] is a promising process which converts greenhouse gases CH₄ and CO₂, into syngas - a mixture of H₂ & CO. With GAD, upto 40% conversion of methane has been reported, achieving the energy efficiency target of 60%. In terms of energy cost, it is in the range of 1-3 eV/molecule of CH₄ compared to 20-120eV/molecule of CH₄ for other plasma sources such as dielectric barrier discharges which has energy efficiency lesser than the target 60% [8].

In addition to dry methane reforming, GAD has also been employed for CO₂ dissociation into CO and O₂ [8]. It has been reported that using GAD for dissociation of CO₂ at atmospheric pressure, one can achieve energy efficiencies as high as 60% whereas other plasma sources such as micro wave plasmas can yield a maximum of 40% energy efficiencies at atmospheric pressure conditions [8]. It is worth mentioning that the GAD breaches the maximum possible energy efficiency based on thermodynamic limit. All other non-thermal plasma sources such as DBD are still below the thermodynamic limit.

GAD is also used in applications which can produce 99.999 % pure H₂ using water splitting. It should be noted that, water vapor splitting in traditional thermal plasma needs a relatively high temperature of around 1000 K [23]. Compared to conventional electrolysis process which uses planar electrodes for electrolysis, plasma-assisted water splitting process could potentially produce 1000 times more hydrogen throughput for the same dimension of electrolyser [23]. We believe that is due to its the plasma volumetric process which happens in the plasma reactor versus the electrode surface reactions in conventional electrolysers. Among plasma based systems, RGA based electrolysers produce the highest H₂ throughput. Researchers have reported that, hydrogen production rate using RGA was 41.3 μmol per seconds where as it was 0.2 μmol per second using DBD [23].

GAD also finds its application in hypersonic propulsion systems where hydrocarbon based fuel is used.

Table 2 .Applications of Rotating Gliding Arc

Applications	Remarks on Performance	References
Dry methane reforming	Energy efficiency > 60% at 40% conversion	[27,28,30]
CO ₂ reduction through its dissociation	Energy efficiency of 65 % at 20% conversion	[9,18,33]
Enhancement of Combustion	Energy consumption from gliding arc can be about 1~2 % of total energy from combustion	[17,29,30,34]
Material treatment	Maximum fracture resistance achieved is 490Jm ⁻² increasing adhesive strength at interface by factor of 2-2.5	[35]
Air sterilisation	E-coli cells killed in <3mins with reduction of 7 logarithm units of bacterial population within 30s	[32]
Waste water disposal	The discolouration rate of AO7 is 99.3% for a concentration of 100 mg/L, and decrease of the COD of the solution by 37.9%.	[31]
Water splitting for H ₂ generation	H ₂ yield of 12% or 0.96g/kWh	[23]

One of the major problems in hypersonic propulsion systems, is that gas residence times is of the same order of magnitude as that of ignition delay [29], causing failure of ignition in the combustor. This limitation is addressed by accelerating the ignition thermally or kinetically by sourcing elevated temperatures, radicals, ions, excited species and/or electrons through plasmas. For such combustion enhancement applications, predominantly GAD [17,29] is used. As an added advantage, fuel subjected to plasma generates Hydrogen which further improves combustion [30].

Recently, GAD is also used to destruct aromatic hydrocarbons, which are unwanted hazardous by-products of gasification, generally referred as tars. Destruction of tars using GAD enables gas cleaning without the need for separation of these tars from the product gas [5,21].

During last few years GAD has been extensively used for waste water treatment also. Oxidative power is observed in active species such as HO•, NO• and O₃ generated during GAD plasma process [31]. Availability of reactive species, photons and UV, GAD is also extensively used to inactivate various microorganisms and to rapidly achieve good sterilization effects in short time scales [32].

3.4 Conclusions

GAD has been studied by various researchers towards addressing niche applications using gas phase reactions. GAD has shown increased energy utilisation compared to the other plasma variants. Apart from the electrode geometry, it is shown that fluid mechanics also play a critical role in the plasma reactor. With various geometry and configurations explored in the literature, there is significant scope towards improving the overall efficiency; impacting the specific energy requirement for a given duty cycle.

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