Observation of Arc Rotation and Voltage characteristics in Rotating Gliding Arc

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Abstract: A new rotating gliding arc (RGAD) type reactor is developed without using magnets, with novel approach to electrode configuration suitable for gas cleaning applications. In this work, it is attempted to understand and verify the influence of gas flow dynamics on voltage characteristics and dynamics of the rotating gliding arc. Experiment is conducted using Argon gas by varying (a) 'number of tangential entry holes (NH)' of gas vortex and (b) 'flow rate (Q)'. Influence of gas flow dynamics is observed and verified by the (a) existence of linear functionality between arc rotational frequency (f_{arc}) and Reynolds number (Re) and (b) effect of gas flow nature (laminar or turbulent) and its disturbance on the nature of voltage waveforms (regular or irregular periodicity). This work is important for understanding and optimising the reactor for specific applications.

Keywords: Rotating Gliding Arc, Gas dynamics, Arc dynamics.

1. Introduction

In recent times, non-thermal plasma is extensively being used in applications involving low temperature chemical reformations which are not thermodynamically favoured in the absence of plasma [1,2]. However, non-thermal plasmas such as glow discharge, corona & silent discharge and dielectric barrier discharge (DBD) show limitations interms of power, selectivity and operating parameters such as reactor pressure, residence time and operating temperatures [3,4]. These disadvantages of non-thermal plasma systems are overcome by gliding arc discharges (GAD) which have very high electron density compared to DBD and corona [5–7]. Traditional planar diverging GAD is reported to have short cutting of gas from plasma plane and low gas residence time [3]. In order to overcome these drawbacks, a rotating gliding arc (RGAD) without using magnetic field has been developed in our lab. Novel and simple electrode configuration is designed compared to the existing ones in literature [9–17]. To our knowledge, no studies have been carried out yet on the effect of number of tangential entry holes (NH) and flow rate (Q) on arc dynamics and electrical characteristics. As a first step of characterising the designed RGAD reactor in our lab, it is attempted in this work, to study the influence of the control parameters such as gas flow (Q & NH) on arc rotation (f_{arc}) and voltage waveform using argon gas powered by AC-20 kHz. First principle cold flow simulation approach is taken up to link gas flow to the observed arc rotation.

2. Materials and Methods

Fig. 1-(a) shows a schematic representation of the RGAD reactor indicating the functional parts. Gas could be fed through a main inlet port of diameter (D_{in}) 5mm and then through multiple tangential inlet holes (NH) each of diameter 1.6mm drilled in a swirl disc made of steel as shown in Fig. 1-(b), enclosed in MS flange and sealed with silicon O-rings. The bottom outlet is offset from the centre. The reactor wall made of Quartz cylinder has inner diameter D = 40 mm and height 80 mm. Electrodes were circular ring made of aluminium wire of diameter (dia) 2.5 mm. The high voltage (HV) and ground electrodes were configured as shown in Fig. 1-(c). Ground electrode of dia 30 mm was held flat, perpendicular to z-axis as shown in Fig. 1-(a) and HV electrode of dia 35 mm was inclined such that its horizontal projection would be 30 mm. The arc was ignited at the shortest gap between two diverging electrodes. The arc was observed to glide and rotate thereby elongating the arc over the time of rotation due to electrode configuration as in Fig. 1-(c). This rotation could be due to the influence of the gas vortex, which is verified in this work. Throughout the experiment, the electrodes were positioned as shown in Fig. 1-(a). The shortest gap between the two electrodes was 6mm and the longest gap was 25mm. Fig. 1-(d) shows the 3D model used in cold flow simulation.

Electrodes were powered with AC 20kHz power supply (PVM500-4000, M/s Information Unlimited). The system was fed with Argon using MFC (MCR-100SLPM, Alicat Scientific) at ambient conditions. Voltage probe (Tektronix P6015A) was used to record voltage waveforms whose signal was recorded using four-channel oscilloscope (Tektronix TBS 2074) at a sample rate of 1 GHz. A high-speed camera (Chronos 1.4, kron Technologies) equipped with Canon lens (EF S18-55 IS STM) was used to record the arc rotation at 1057 fps and 100µs exposure time. Electrical characteristics and high-speed camera capture were synchronised by a trigger signal generated from function generator (Tektronix AFG 2021). Fig. 2 shows the block diagram of the experiment setup and Table 1 shows the experimental parameters and conditions used in this study.

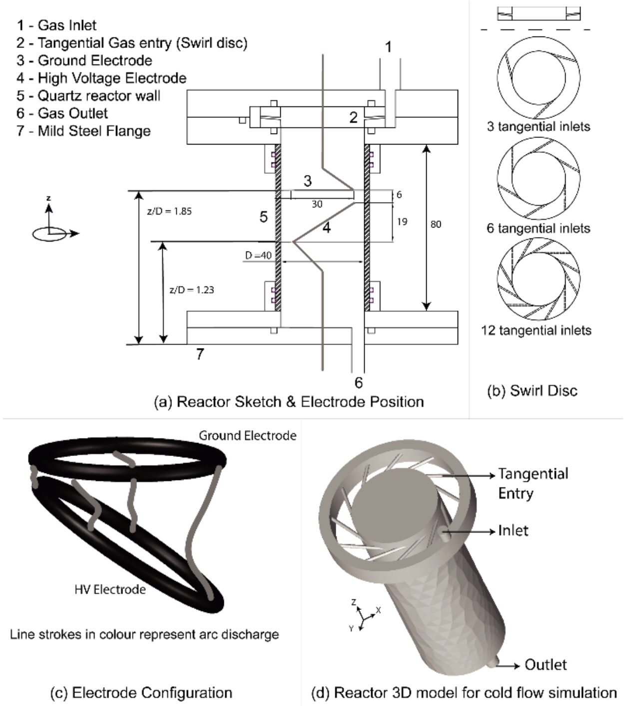

Fig. 1 Design of reactor and electrode configuration

The Reynolds number (Re) is defined based on the average of area weighted tangential velocity (V_t) at z/D = 1.23 and 1.85 (position of the electrodes) as shown in Equation 1. The argon gas density (ρ) and dynamic viscosity (μ) at room temperature were used for the calculation. Cold flow simulation was performed using Reynolds-Averaged-Navier-Stokes (RANS) turbulent model (Realizable k-ε) in commercial package. Reactor inner diameter was chosen as hydraulic diameter 'D'. Following boundary conditions were used for the simulation; (1) Inlet: Mass flow boundary type with flow rate given in kg/s; (2) Outlet: Pressure boundary type and (3) Wall: No slip shear condition with standard wall functions. During the transient simulation, the residual of the velocity fluctuation was monitored and the data for calculation were considered beyond the time at which the residual became minimum and throughout then was approximately constant.

$$\mathrm{Re} = \frac{\rho V_t D}{\mu} \tag{1}$$

Arc rotational frequency (f_{arc}) is calculated by performing fast Fourier transform (FFT) on time resolved voltage waveforms. Characteristic frequency of the power supply (19 kHz) was filtered before performing FFT. Arc rotational frequency was also calculated by observing the rotating arc through high speed camera and thereby using the captured frames for calculation as shown in Equation 2.

$$f_{arc} = \frac{\text{Frame per second}}{\text{(No. of frames in single rotational cycle)}} \tag{2}$$

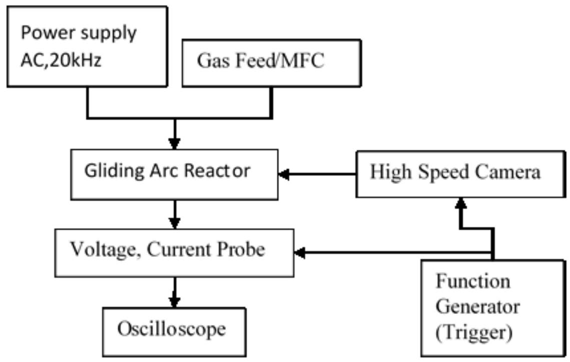

Fig. 2 Block diagram of experiment setup

Table 1. Experiment conditions

Control Variables	Conditions	Unit
Number of tangential entry holes (NH)	3, 6 and 12	No.
Argon flow rate (Q)	2, 5, 10, 25, 35 and 50	LPM
Constant variables		
Gap between the electrodes Position of electrode Power supply characteristics		

3. Results and Discussion

Fig. 3 shows the calculated Reynolds number for the experimental conditions using results from cold flow simulation. The flow is laminar for Re<2100 and turbulent for Re>4200. For NH= 3, the flow is laminar at Q = 2, 5 and 10 and is turbulent for Q≥25. For NH=6, the flow is laminar at Q<25, transitional at Q=25 and turbulent at Q>25. For NH=12, the flow is laminar at Q≤25, transitional at Q=35 and turbulent at Q≥50.

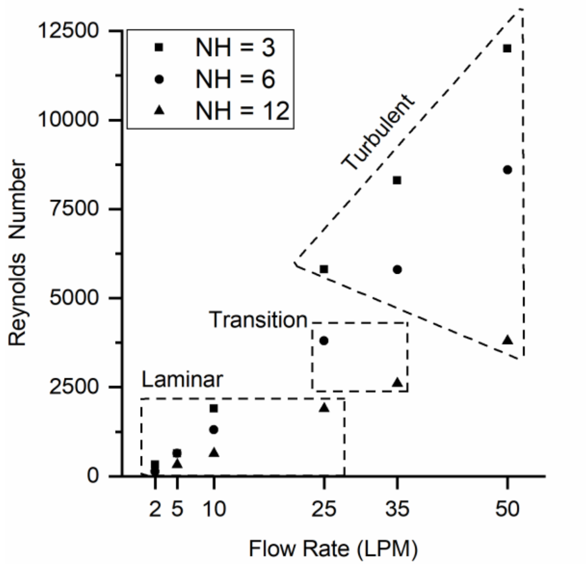

Fig. 3 Calculated Reynolds number for Experiments

Fig. 4 shows the time resolved voltage waveforms for all the experimental conditions. At Q =2 & NH =12, the arc did not rotate and was anchored as shown in Fig. *4*-(c). Hence, the experimental condition Q=2 is not considered for the analysis and discussion. The voltage drop is related to related to length of the arc. As arc length increases, the voltage drop increases and goes to the minimum at the initiation of the arc during which the arc length is the shortest. As shown in Fig. 4, the voltage waveform pattern is regular and periodic for NH = 3 and 6 at Q≤10LPM and for NH = 12 at Q≤25LPM. When gas flow rate is increased further, the regularity in the voltage waveform disappeared leading towards irregular periodicity as could be seen in Fig. 4. It is interesting to note that this voltage irregularity behaviour follows the nature of the gas flow based on defined Reynolds number, i.e., the voltage waveforms show a regular pattern when the flow regime is laminar and become irregular when flow regime is turbulent or transitional as evident from Fig. 3 and Fig. 4. This shows that the Re defined in this work based on tangential velocity has good agreement in indicating the nature of voltage waveform fluctuation. The gas flow regime (laminar/turbulent) and its corresponding voltage pattern (regularity) is summarised in Table 2. Offset outlet can also cause disturbances due to asymmetric axial velocity profile, recommending centred outlet for the future.

Table 2. Gas flow nature and Voltage waveform nature for experiment conditions

Q→	5	10	25	35	50
NH 3	L/R	L/R	T/IR	T/IR	T/IR
NH 6	L/R	L/R	T/IR	T/IR	T/IR
NH12	L/R	L/R	L/R	T/IR	T/IR

Gas flow: L – Laminar, T – Transition or Turbulent;
Voltage: R – Regular, IR – Irregular

Table 3 shows f_{arc} calculated from both FFT of voltage waveform and high-speed camera methods, which matches very well. Fig. 5 shows the plot of defined Re Vs f_{arc} (FFT method). With R^2>0.95, a linear fit function is established relating the gas flow and the arc rotation for individual NH. This indicates the good influence of gas flow dynamics on arc dynamics.

Table 3. Summary of calculated Arc rotational frequency

NH	Q	f_{arc} (High Speed Camera)	f_{arc} (FFT of Voltage waveform)
3	5	3.71	3.75
3	10	5.07	5.00
3	25	8.62	8.75
3	35	11.42	10.62
3	50	16.50	14.37
6	5	3.20	3.12
6	10	4.75	3.75
6	25	9.80	9.37
6	35	12.54	12.50
6	50	19.63	18.13
12	5	2.45	1.86
12	10	3.71	3.75
12	25	6.23	6.25
12	35	8.12	8.13
12	50	10.79	10.62

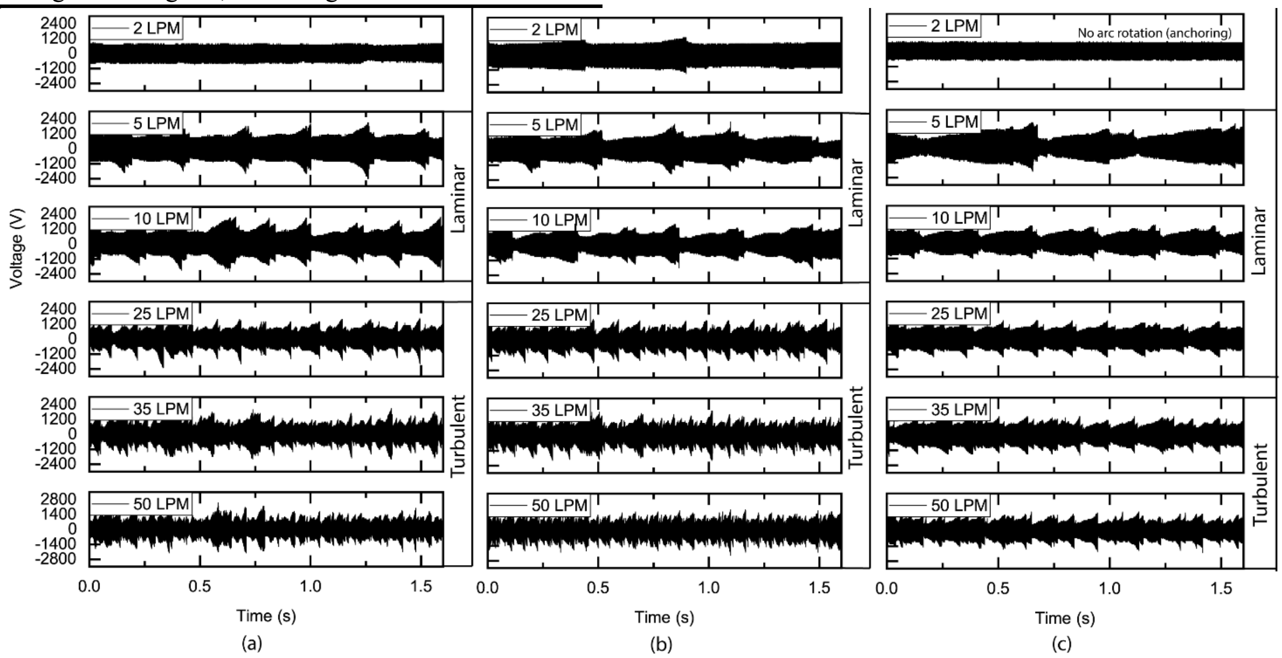

Fig. 4 Time resolved voltage waveform at experiment conditions (a) NH = 3; (b) NH = 6; (c) NH =12

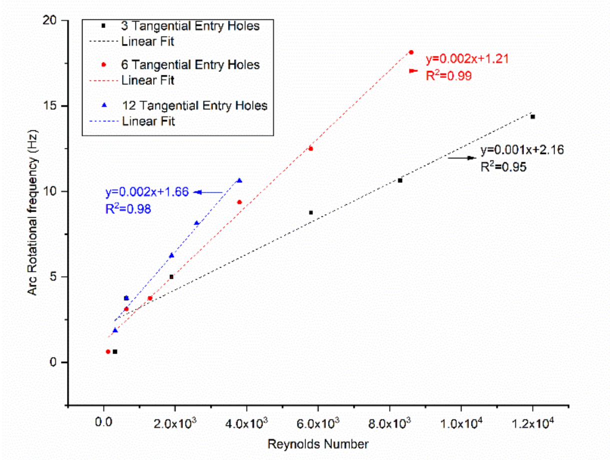

Fig. 5 Reynolds number vs Arc rotational frequency

4. Conclusion

1) Reynolds number defined in this work shows linear functional relation with f_{arc}.

2) The nature of gas flow (laminar or turbulent) has influence on the arc dynamics which is visible in the voltage waveform pattern. The voltage waveform changes from regular to irregular periodicity for experimental conditions at which the flow nature was calculated to be turbulent from cold flow simulation.

The results and observations become preliminary evidence for influence of reactor's fluid dynamics on the arc' electrical and physical characteristics. This understanding could provide scope to use results of CFD simulation for calculating the arc rotational frequency and for predicting the fluctuation behaviour of voltage waveform, as in real field operations without using costlier diagnostic equipment. Understanding the effect of "number of tangential entry inlets" as control parameter will enable to optimise the reactor by improving mixing.

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