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PARTIALLY PREMIXED FLAME REACTIVE FLOW CHARACTERIZATION IN A BLUFF BODY BURNER

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ABSTRACT

The present work aims the characterization of a natural gas/air partially premixed flame (PPF) reactive flow in a bluff body burner under laminar conditions in equivalence ratio of 2.1, 1.7 and 1.2. The laboratorial bluff body burner is composed of a central outflow for the premixed reactants and an annular air flow. The latter allows for the stabilization of the flame meanwhile it prevents external aerodynamic influence on the behavior of the flame. For the velocity field measurements, a 2-D Particle Image Velocimetry, PIV, optical diagnostic system is employed. The PIV system comprises of two Nd:YAG lasers with an output wavelength of 532 nm. Titanium dioxide particles, TiO_2, are used as seeding particles in the premixed flow. The displacement of the seeding particles between two laser pulses with a known short time difference allows a planar velocity field determination. The stored images are processed using a software integrated with the system in order to obtain the medium velocity field. The software uses statistic data to obtain the correlation between two images acquired in an interval of time of an overlapped interrogation window. The major objective of this study is to examine the flame velocity field of laminar partially premixed natural gas and air flames in rich conditions. Three premixed flames under rich conditions have been studied in the present work with equivalence ratios of 2.1, 1.7 and 1.2 respectively. The study focused on: (1) analyze the instantaneous velocity flow field of the three partially premixed flames, (2) analyze the mean velocity flow field formed from the instantaneous flow fields and (3) analyze the velocity behavior along the center line of the flame.

INTRODUCTION

Partially premixed flames (PPFs) are established in a flow upstream of the reaction zone when less than stoichiometric amount of oxidizer is mixed with fuel, in which additional oxidizer is available to diffuse into the flame and provide complete combustion [1-3]. PPFs are usually described as hybrid flames with the characteristics of both non-premixed (or diffusive) and premixed flames [4]. It is a dominant phenomenon in combustion of real combustors and due to their stability, safety, and emissions control, PPFs are observed in a variety of practical situations, including lifted flames in furnaces, industrial burners, gas-fired domestic appliances, and recently in compression ignition engines [5, 6], therefore, it is one of the main focuses of combustion research [7]. Compared to lean premixed combustors, partially premixing has the potential to increase flame stability, since flashback phenomenon does not occur, and compared to traditional non-premixed burners, PPFs promotes the reduction of pollutant formation [5].

Experimental and numerical studies have provided detailed measurements of flame propagation [6, 8, 9], nitrogen oxides [1, 10, 11]; flame temperature [11-13], equivalence ratios [2, 3, 5, 14, 15] and flame structure [5, 8, 15-18].

Although most of the PPFs combustion applications operate under turbulent regimes flow fields which increase the mixing process, a deep understanding of laminar combustion is fundamental the modeling of turbulent flames [2, 3]. Even though the previous mentioned achieved progress, there is still a certain interest in the combustion community to continue working on the detailed analysis of these simple configuration flames [2]. The study of PFFs provides additional step toward gaining a better understanding of combustion processes [19].

An experimental study was performed to investigate the velocity flow fields of partially premixed flames varying the equivalence ratios. Three premixed rich conditions have been studied in the present work with equivalence ratios of 2.1, 1.7 and 1.2 respectively. The instantaneous and mean velocity flow fields of a natural gas and air partially premixed flames were analyzed such as the velocity behavior along the center line of the flame. This work intended to produce results which will provide experimental data for the next applications foreseen to the burner.

EXPERIMENTAL SETUP

The experimental setup is schematically shown in Figure 1. The burner project was elaborated based on the burner described in [20]. Some modifications were carried out to adapt it to the requirements and working conditions to be studied in this paper. This type of burner enables to stabilize flames in different combustion regimes on its work zone and allows optical diagnostics techniques to be applied.

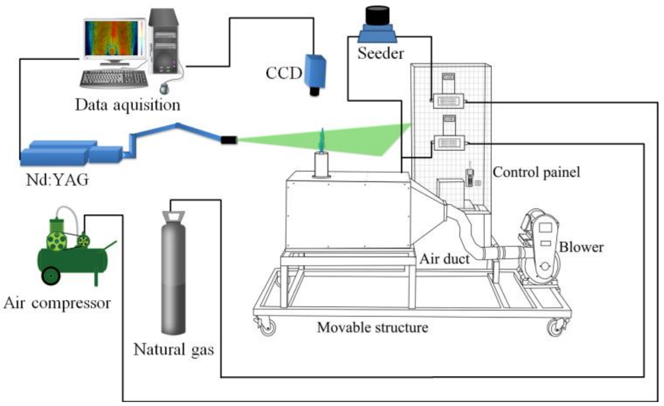

Figure 1 Schematic of the experimental setup.

A premixed mixture of natural gas and air flows through a center nozzle with 7.30 mm of diameter, and the bluff body diameter is 25.10 mm. A detailed schematic of the burner is presented in Figure 2. The diameter of the external tube where air co-flows in the annular channel at standard atmospheric pressure is 86.50 mm. The air co-flows with an axisymmetric profile, aiming to protect the flame from ambient air fluctuations. The flow uniformity is obtained by using honeycombs in the annular channel upstream of the outlet. Mass flow meters are used to control the fuel and air rates to produce the desired pre mixture. Natural gas was fed into the burner through a set of controllers and manual valves before reaching the inner exit of the burner.

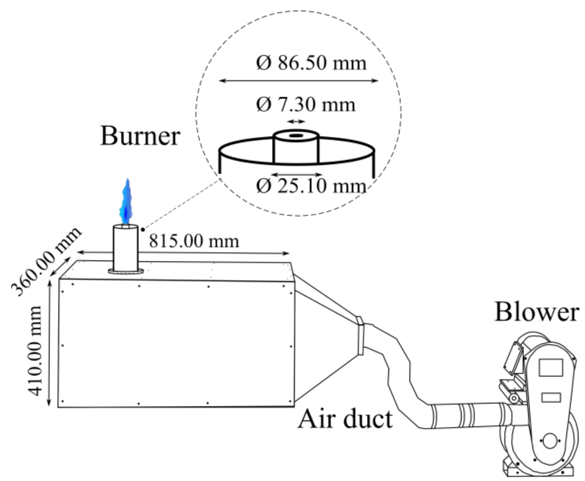

Figure 2 Detailed schematic of the bluff body burner.

For the velocity field measurements, the non-intrusive optical diagnostic system technique, 2-D Particle Image Velocimetry, PIV, was employed. The PIV system comprises of two Nd:YAG lasers with an output wavelength of 532 nm. A CCD camera, integrated to the system, was employed to acquire the images of the flow. The camera can store the first image (frame) fast enough to be ready for the second exposure. The camera captures the Mie scattering of laser light from the seeding particles. Titanium dioxide particles, TiO_2, introduced into the premixed air flow, are used as seeding particles in the premixed flow. The displacement of the seeding particles between two laser pulses with a known short time difference, allows for a planar velocity field determination. The velocity vector field is calculated by processing the pairs of particle images. In this work 170 pairs images was taken in the RAM memory of the camera at 10 kHz of acquisition rate. The stored images are processed using LaVision 7.2 software integrated with the system in order to obtain the medium velocity field. The software uses statistic data to establish the correlation between two images acquired in a time interval of an overlapped interrogation window.

RESULTS AND DISCUSSION

In the present study, natural gas flow was maintained constant at 0.010 g/s and air was introduced to form a premixed mixture with total amount of flow rates, equivalence ratios, instantaneous velocities and Reynolds number of the premixed flow and the mean velocities of the annular air are presented in Table 1. The co-flowing air velocity for the second and third cases are correlated with the premixed flow velocity meanwhile in the first experiment it is not correlated.

Seeding particles of titanium dioxide were inserted into the premixed and annular air flows. Three instantaneous images were chosen between a range of 170 images for each cases. The results of instantaneous and mean velocities of natural gas and air partially premixed flames are shown and discussed in this section in order to perform the flow field characterization obtained with PIV optical technique.

Table 3 Operating conditions performed

Case	Flow (g/s)	φ	Velocity (m/s)	Reynolds	Annular air (m/s)
1	0.090	2.1	2.50	920	1.40
2	0.120	1.7	3.10	1230	2.80
3	0.150	1.2	3.50	1540	3.40

Instantaneous flow field analysis

Three instantaneous images of the velocity distribution are presented in sequence for the premixed conditions. In case 1, either images show a uniform distribution along the inner flow produced by the partially premixed flame, as presented in Figure 3(a). The mean annular velocity of the flow measured with PIV is approximately 1.40 m/s at the bottom of Y axis at x/D = 0 position, where x/D is the center nozzle.

Case 2 instantaneous velocity field is presented in Figure 3(b). The three images show similar inner flame flow and do not display vectors on the flame contour, probably due to the difference of density between the premixed flame region and the diffusive flame.

In case 3, as shown in Figure 3(c) the average velocity of the annular air is 3.40 m/s and the flame flow is 3.50 m/s. The flow field of the flame in this case presents more spurious vectors, probably due to the higher interaction of the flame with the external air at the recirculation zone.

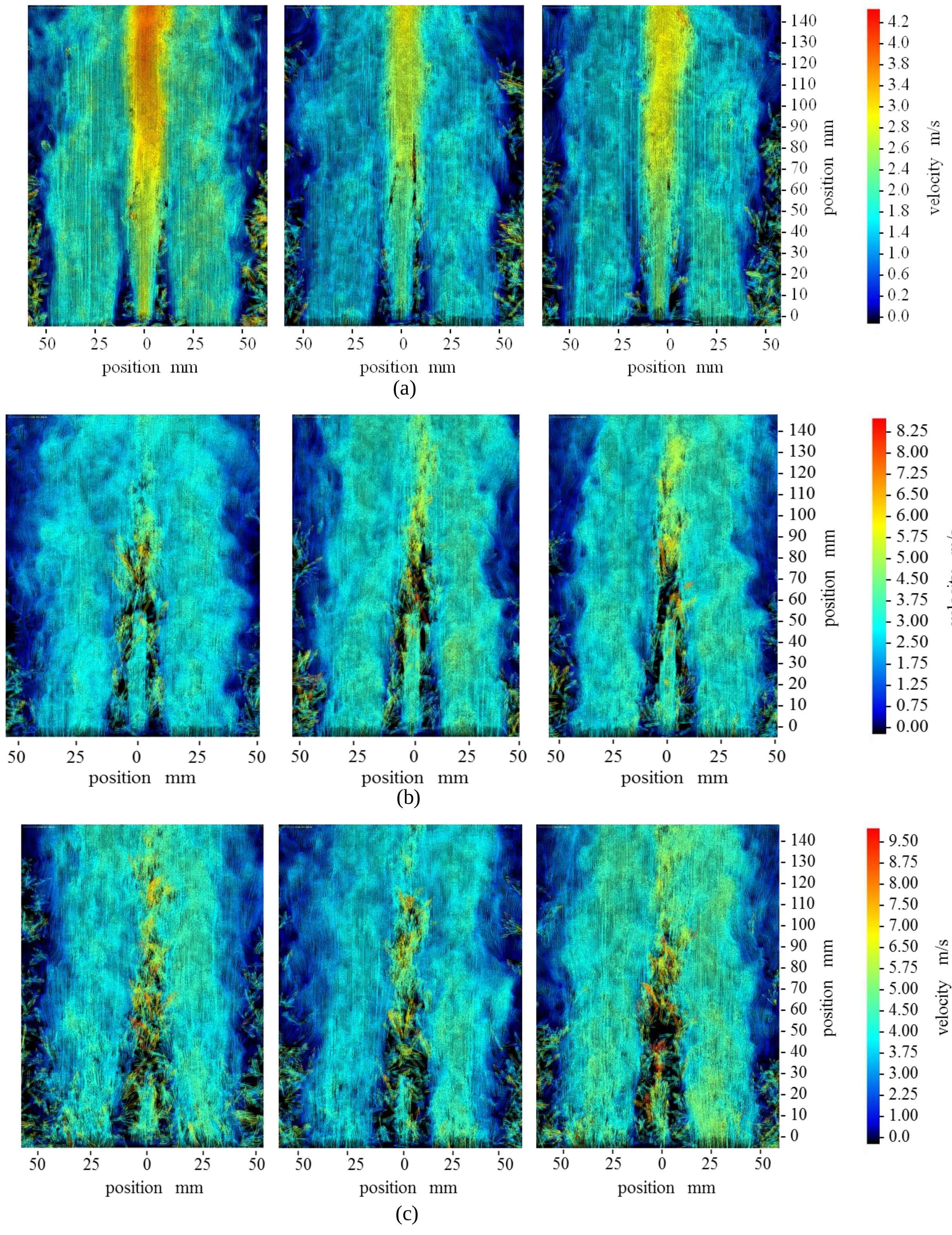

Figure 3 Instantaneous velocity flow field of (a) case 1, (b) case 2 and (c) case 3.

Mean flow field analysis

The mean velocity flow field distribution of case 1 is presented in Figure 4. The premixed flame produced in the inner flow has approximately 70 mm height and is surrounded by annular air forming a recirculation zone in the basis of the flame in Y axis positions between 0 to 30 mm.

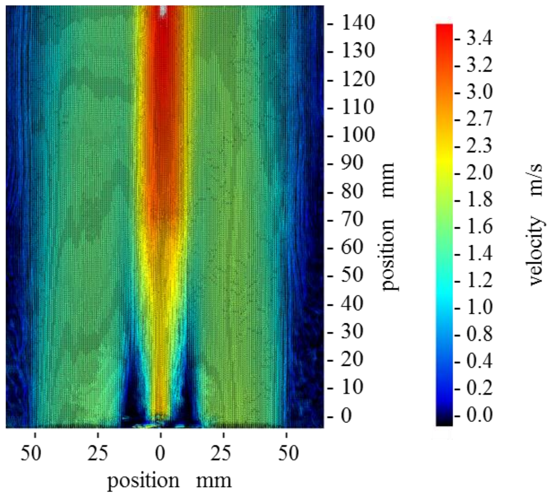

Figure 4 Mean velocity flow field of case 1.

The mean flow field velocity of case 2 is presented in Figure 5. The premixed flame height is approximately 50 mm. It is possible to see a correlation of velocities between the flame and the annular air flows. The recirculation zone, approximately located between 50 mm to 70 mm along the Y axis, is more intense in case 2 compared to case 1.

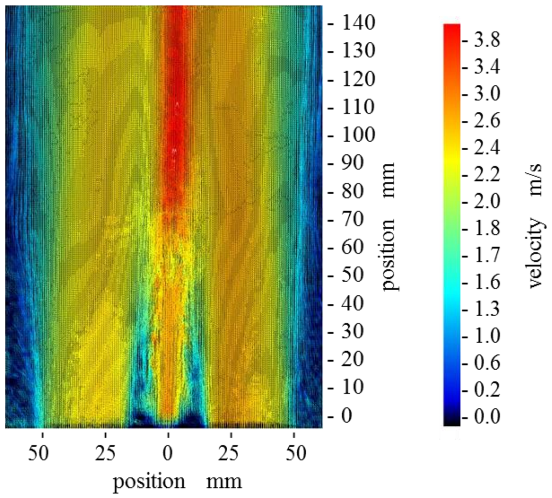

Figure 5 Mean velocity flow field of case 2.

The mean velocity flow field of case 3 is presented in Figure 6. The premixed flame height is 30 mm approximately. This experiment presents the higher recirculation zone in comparison to the previous cases. The flow velocity at the bottom of the flame is 3.50 m/s. The temperature increases after the diffusive flame region due to the energy liberation of combustion, as a consequence of intermediate reactions of carbon monoxide and hydrogen oxidations. This phenomenon, valid for the three cases under considerations, promotes the increase of the velocity flow. The difference between them is due to the different velocity of the mean flame jet, which influences the recirculation zone intensity, and the premixed flow equivalence ratio that promotes the increase of the temperature, consequently increasing the velocity upward the diffusive flame.

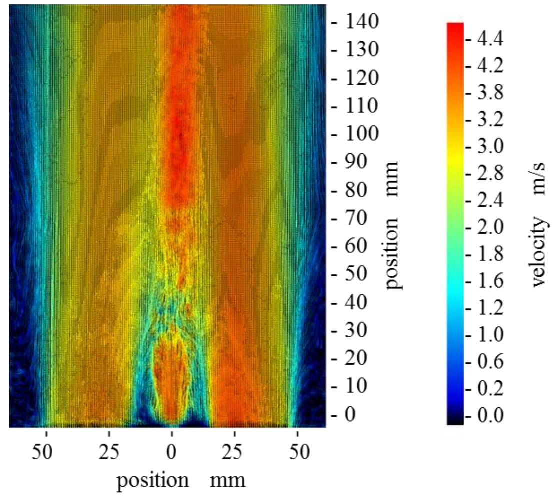

Figure 6 Mean velocity flow field of case 3.

Analysis of case 1

The profile of the flow velocity as a result of the mean flow field post processing, along the center line of X axis (x/D = 0), is presented in Figure 7 for case 1. The velocity is high at the nozzle exit, decreases along the flame, probably due to the interaction with the recirculation zone, and increases close to the top of the premixed flame at 70 mm. Thereafter the velocity continuously increases as the temperature and energy liberation along the flow increases until reaching the maximum value of approximately 3.51 m/s at the top of the flow field region of study.

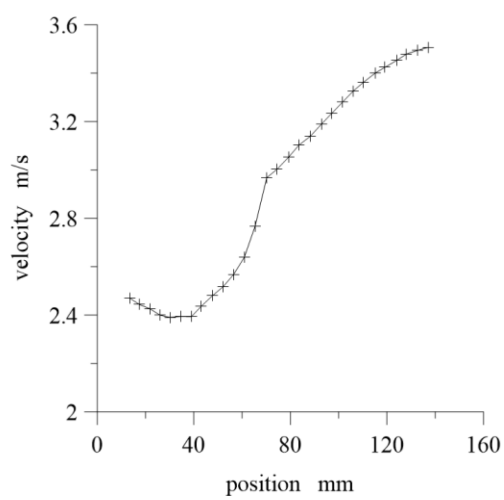

Figure 7 Flow velocity profile along the center line of X axis of case 1.

Analysis of case 2

Figure 8 presents the flow velocity profile along the center line of X axis for case 2. The flame height is approximately 50 mm and as it was shown in case 1, the velocity value decreases along the premixed flame until reaching the region of high interaction with the recirculation of combustion product gases. Similarly to the previous case, the flow velocity starts increasing close to the top of the premixed flame. In this case, the velocity increases until reaching the maximum value of 3.69 m/s at the height of approximately 90 mm. Further, the turbulence from the annular air promotes an inversion of the velocity behavior.

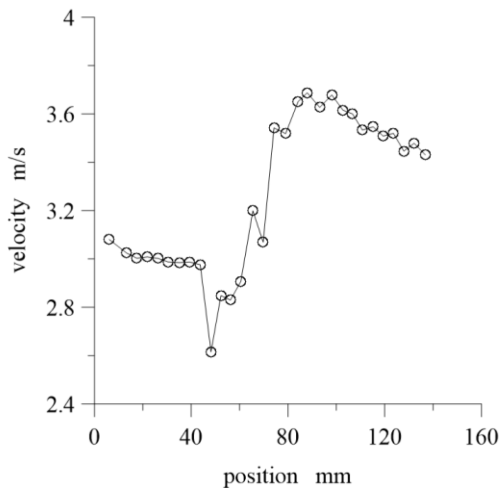

Figure 8 Flow velocity profile along the center line of X axis of case 2.

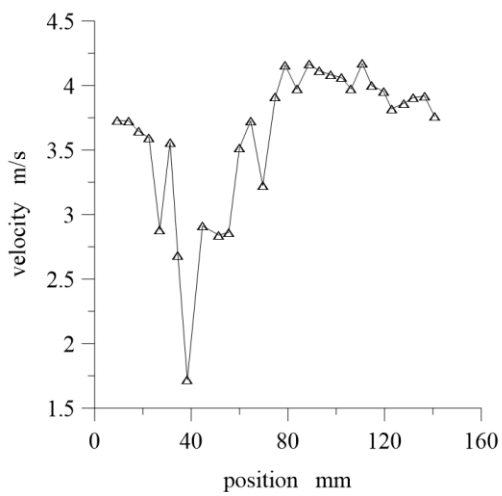

Figure 9 Flow velocity profile along the center line of X axis of case 3.

Analysis of case 3

The flow velocity profile along the center line of X axis is presented in Figure 9 for case 3. The flame height in this case is approximately 30 mm and, as it was shown in the previous cases, the flow velocity value decreases along the premixed flame until reaching the region of high interaction with the recirculation of combustion product gases. Similarly to the previous cases, the flow velocity starts increasing close to the top of the premixed flame. The strong interaction zone between the premixed flame and the diffusion flame is observed in the figure as it provokes flow velocity fluctuations. The velocity increases until reaching the maximum value of 4.2 m/s at the height of approximately 80 mm. Further, the turbulence from the annular air promotes an inversion of the velocity behavior.

The higher velocities of case 3 compared to the other cases are due to the higher initial flow velocity leading to a more intense recirculation zone thus affecting the flame shape and the interaction with annular co-flowing air.

CONCLUSION

In the present work, three cases of partially premixed flames under rich conditions, with equivalence ratios of 2.1, 1.7 and 1.2 respectively, have been studied in a bluff body burner with annular air in co-flow configuration. 2-D PIV non-intrusive optical technique was applied in this work for the characterization of a natural gas/air partially premixed flame reactive flow in a bluff body burner under laminar condition. The instantaneous velocities, the mean flow field velocities and the velocity behavior along the center line of the flame of the three cases were presented.

It was possible to infer that the velocity flow increases, upward the diffusive flame region, due to the gain of temperature promoted as a result of the carbon monoxide and hydrogen oxidations reactions. The difference mean jet flame velocity and the premixed flame equivalence ratios of the three cases presented influences the velocity flow fields due to aerodynamic and chemical interactions in the recirculation zone and in the region of interaction with annular air.

The flow field velocity values of the three cases decrease along the premixed flame until reaching the region of high interaction with the recirculation of combustion product gases. Upwards the velocity profile increases almost linearly for case 1 while occurs fluctuation of the velocity behavior until the end of the Y axis for case 2 and 3.

The experimental results presented high resolution images and provided mean flow field velocity profiles data for the burner characterization which allows future appliance to operate under different conditions and regimes.

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