Computational Investigation on Design of Scramjet Combustor – A Review

Kumari Ambe Verma, K. M. Pandey, K. K. Sharma

Abstract— Supersonic combustion is carried out primarily in air breathing engines. Atmospheric air is used as an oxidizer and fuel are commonly stored within the system. No moving parts are available in the scramjet engine, which gives higher thrust to weight ratio compared with any other propulsion engines. Different techniques and approaches are used for getting better results in the form of improved mixing, momentum, drag etc. The problems present in the combustor can easily be identified with the help of boundary layer parameters. Small improvement can lead to better performance. One of the technique is by using vortex generator. It creates vortices in the lateral plane. Turbulence can also be generated with the help of wedges, ramp, pylon etc., inside the combustion chamber. So the review article is focused entirely on the effects of boundary layer performance parameters due to implementation of vortex generator in the supersonic combustion ramjet engine (scramjet) at different locations with variable sizes. Basic principle behind use of vortex generator is the vortex formation in the downstream to overcome separation and drag. Geometrical shape is a major concern on vortices formation, so different kind of geometrical shapes have been taken for study such as standard micro ramp, dissymmetric micro ramp, slotted micro ramp, cantilevered micro ramp, swept micro ramp, unswept micro ramp, micro vanes, pylon and ramped vane type of vortex generators. To summarize the entire literature review. It is seen from the literature review that standard micro ramp can help in improving momentum deficits and drag however slotted micro ramp can improve mixing performance. Ramped vane vortex generator gives overall performance of boundary layer in supersonic flow field.

Index Terms— Scramjet combustor design, Vortex generators, Micro-ramp, Flow separation, Drag.

1. INTRODUCTION

Scramjet (supersonic combustion ramjet) engine is one of the most interesting re-search area in the near future [1]. Scramjet is designed for hypersonic flow field and thrust is produced by combustion of fuel and air. Proper mixing in the combustor is the major issue to improve the effectiveness of the engine. There are no moving parts available in the air breathing engine (scramjet) because of its high speed flow so different types of shock and vortices can help to improve mixing however flow separation is also present due adverse pressure gradient. Shock induced by the adverse pressure gradient is the prime cause of flow separation and it leads to pressure loss, drag formation and distortion of flow.

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Kumari Ambe Verma, Research Scholar, Department of Mechanical Engineering, National Institute of Technology, Silchar, Assam, India (E-mail: ambe.verma@gmail.com)

K. M. Pandey, Professor, Department of Mechanical Engineering, National Institute of Technology, Silchar, Assam, India (E-mail: kmpandey2001@yahoo.com)

K. K. Sharma, Associate Professor, Department of Mechanical Engineering, National Institute of Technology, Silchar, Assam, India (E-mail: kksharma1313@rediffmail.com)

Series of experiment and numerical simulation have been done to alleviate the flow separation issue. Different injection techniques (prime focus on transverse injection) and many geometry designs with wedge, cavity, ramp, pylon etc. have been chosen to ameliorate the flow field. As per the performance of plenty research in the field of fuel-air mixing in supersonic flow regimes, Drag force and mixing efficiency are two different and opposite sides of performance parameter [2]. In this review paper, various types of vortex generator devices are selected from the author's re-search articles across the world to summarize the boundary layer characteristics with different height and location in the flow field.

II.EFFECTS OF VARIOUS VORTEX GENERATORS & RESULTS

The vortex generator (VG) is a functional control device for boundary layer improvement. In 1947, Vortex generator was first used by Taylor. Separation of boundary layer, Drag effects, momentum loss and adverse pressure gradient etc. are approximately eliminated by different sizes of VG. Detailed review is summarized in the below section.

A. Standard Micro-Ramp Vortex generator

Ramp base geometry gives good agreement towards vortex generation. Experimental investigation done by H. Babinsky et al. [3] found multiple pair of vortices behind micro-ramp which helps to form low and high momentum region wakes. Higher momentum deficiency (Drag) was seen over larger ramp size so that author suggested to choose smaller device. Inflow condition is also important parameter for vortical flow. Different inlet condition is influenced the micro vortex generator (MVG) in supersonic ramp flow reported by Yonghua Yan et al. [4]. Author found three different turbulent inflow profile in front of the MVG with different boundary layer thickness. Ring like vortical structure in the micro-vortex generator was significantly more influenced by the inlet condition. Interaction between shock wave and ring like vortices can control the boundary layer separation found in computational results. Vignesh Ram P.S. et al. [5] presented the effect of vortex generator (VG) in the flow field around the cylindrical protrusion. Number of cases over different Mach number has been examined to check drag effect. Cylindrical protrusion with VG gives enhanced flow field compared with without VG. All of the cases, author found great reduction in aerodynamics drag therefore Control

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of shock wave boundary layer interaction throughout Mach number can be easily done by introducing Vortex generator. Control of oblique shock wave boundary layer interaction over micro ramp is explored by Charles W. Pitt Ford and Holger Babinsky [6]. Flow field around vortex generators has been broadly examined by experiment with the help of various micro ramp size and found that separation cannot totally eliminated by the device, it only terminates the induced separation. Higher momentum and velocity has been seen near the wall by reason of primary vortices, which could be helpful for downstream interaction reported by the same author [6]. Bernhard H. Anderson et al. [7] used Response Surface Methodology (RSM) to examine shock wave boundary layer interaction control with the help of three micro devices such as standard micro vanes, tapered micro vanes and standard micro ramps compared with conventional inlet boundary layer bleed. Author found larger downstream displacement thickness that helped to grow the passage of internal flow for micro devices and also gives improved boundary layer properties near the wall region due to cascade of counter rotating micro vortices. As well as three dimensional virtual surface also introduced to sustain normal shock. At the end, Anderson and team [7] emphasized to use micro ramp to control flow field at the supersonic inlet for practical use. Bernhard H. Anderson et al. [8] used fail safe techniques for boundary layer flow control over micro array of ramp and vanes type in propulsion system. Strength of micro devices with embedded micro jet can be improved by first generation technique. Flow control was achieved by the variation of mass flow rate of micro jet and jet total pressure ratio and realized, vortex generation over micro ramp can be easily obtained by small amount of high pressure jet injection. Three dimensional incompressible laminar to turbulent transition region behind micro ramp has been explored by Qingqing Ye et al. [9]. Shortfall of momentum was observed in the boundary upwash motion due to primary vortex pair. Secondary vortices was seen nearly wall side, Further vortices pair like tertiary, fourth etc. also followed the wedge type pattern outside of the secondary pair. Kelvin-Helmholtz (K-H) vortices was seen in arc like structure and show deficiency in momentum however there was no importance was observed of K-H in forced transition. Structural studies was carried out in hypersonic flow field, which gives same result as supersonic flow field over micro ramp by R. Saad et al. [10]. Two primary vortices was detected at the micro ramp slant edge and secondary vortices at the foot of the ramp in downstream nonetheless these vortices played important role in the boundary layer separation control. Inlet condition and combustion efficiency has been examined with ramp compression by Takeshi Kanda et al. [11]. Vertical fuel injection gave up to 90% of combustion efficiency and appropriate amount of thrust was not reached due to inferior geometry optimization. High temperature and pressure were attained by the ramp effect in the combustor and this gave good result for inlet also. Design of experiments method was chosen to investigate the downstream shock in the boundary layer properties by Stefanie M. Hirt and Bernhard H. Anderson [12]. Optimum value was display with chord length and larger height for shape factor. Weak vortices was seen during smaller height of micro ramp and reduced chord length also. Strong vortices helped to pull the flow into the wall region. Qingqing Ye et al. [13] investigated the wake flow behavior and mechanism influenced by Reynolds number. Experimental observation was done with the help of tomographic particle image velocimetry. Downstream flow field was stay laminar at subcritical Reynolds number and for supercritical and critical, unsteady wake disturbance was observed moreover transition region was formed because of the rapid growth of boundary layer. Zhang Qinghu et al. [14] explored effect of flow field over double wedge with or without micro ramp. Experimental work was done through Nano-tracer planar laser scattering (NPLS) technique. Larger vortex gave survival of flow over double wedge that was generated by micro ramp. Two type of layer was seen in the boundary layer over double wedge. Upper layer show larger vortices containing smaller vortices (Ellipse-like structures) and lower layer show streak structure. Manan A. Vyas et al. [15] conducted an experimental work to examine boundary layer characteristics over combination of micro ramp and jets. Design of experiments (DOE) analysis has been chosen for reversed-flow thickness and boundary-layer thickness as a response variable. It was found that DOE analysis is not sufficient to examine boundary layer thickness and reversed-flow thickness. Weaker vortices was seen for smaller height of ramp and spacing between two ramps, which result lack of high momentum flow. Addition of micro jet gave improvement in momentum deficiency so Hybrid flow is improved technique to eliminate flow separation. Flow diagnostics with different experimental methods was taken to visualize boundary layer separation by Mohd Rashdan Saad et al. [16]. Flow movement over ramp caused counter rotating vortices, observed in oil-flow visualization. Location of flow separation can be observed by pressure mapping. Investigation between two different micro ramps can give the size and area of the separation region. Two different Mach number was chosen to investigate flow performance over micro ramp by M. R. Saad et al. [17] in supersonic flow field. Flow characteristics was similar in both Mach number however stronger vortices was observed in higher Mach number. Surface flow visualization outcome was entirely different from each other. From both cases, author observed that micro ramp vortex generator is good enough to control the interaction of shock boundary layer in both Mach number flow field. S. Lee et al. [18] explored flow control of shock wave boundary layer with both experimental and numerical simulation. LES identified the shape variation in the structure of primary vortices and eddies formed by turbulent because of shock. Reduction in boundary layer thickness and improved health of downstream boundary layer could be done by introducing only micro ramp in the flow field validated by both LES and experimental. Results also revealed about total pressure recuperation compared with baseline size. Reduction in separation area and displacement thickness obtained by the movement of the ramp towards shock interaction. Overall wake effect was eliminated by the smaller ramp. Interaction between turbulent-chemistry has been presented by Jesse A. Fulton et al. [19] with experimental and two different simulation (RANS and LES) based. Hydrogen Ramp injection was used in supersonic combustion. To stop shock train in the isolator, lower equivalence ration has taken in the combustor. Laminar flamelet theory was used to explore flame holding region. Formation of hole was observed in the flame because of higher scalar dissipation rate nonetheless refilling of flame hole was seen however this gave increase axial vorticity. For combustion point of view, favorable results has been observed but concept did not find good enough for mixing technology. Flame suppression could also be generated because of high strain rate.

B. Dissymmetric Micro-Ramp Vortex Generator

On the other hand Binbin Zhang et al. [20] commented that the distance between counter rotating vortices and height from wall could adversely affect the separation in the flow. To overcome this problem Zhang and team compared dissymmetric micro ramp with standard micro ramp and identified that vortex height of dissymmetric micro ramp was smaller.

C. Slotted Micro-Ramp Vortex Generator

Xiangrui Dong at al. [21] studied wake structure characteristics of micro ramps. Train of vortex ring, pair of counter rotating stream wise vortex tubes and secondary vortices has been seen in the wake of micro ramp. It was observed that energy can be exchanged by main vortex pair in to the upwash and downwash motion. Compared with micro ramp, slotted micro ramp had more complicated wake structures however controlled effect was found better because of additional vortices generated by the slot. Back flow elimination and reduction of profile drag was recognized in slotted micro ramp. Author emphasized that the appropriate location of slot in ramp is more beneficial for flow separation control. Slotted ramp with semi-circular groove used for mitigation of shock induced separation was analyzed by Pushpender Sharma and Santanu Ghosh [22] and inspected that the performance improved by the increment in the both height of the ramp and radius of the slot nevertheless slight reduction in total pressure loss has been identified due to the use of slotted ramp and this is helpful in the reduction of low pressure side region behind of trailing edge of the ramp. Lower liftoff height of vortices in slotted micro ramp has been observed from swirl center trajectory compared with standard micro ramp investigated by Jatinder Pal Singh Sandhu et al. [23]. Reduction in the height of vortices can be done by two ways either using higher radius of slot or increasing taper of slot. Liftoff height of primary vortices is also affected by secondary vortices noticed in helicity contours by the same author. Lesser drag and lower value of displacement and momentum thickness was seen in slotted micro vortex generator for the outer boundary layer. Computational work was carried out to alleviate the flow separation over slotted ramp in the supersonic flow field by Pushpender Sharma et al. [24]. Lesser drag was identified moreover moderate level of lift off was also observed for the pair of primary counter rotating vortices due to slotted ramp. Slotted device gave better performance over standard vortex generator especially in flow separation, when position of the slotted device was nearer to the shock wave boundary layer interaction.

D. Cantilevered Micro-Ramp Vortex Generator

Improved mixing between fuel and air was seen in cantilevered ramp injection examined by Wei Huang and team [2]. Size and angle of ramp also affect the mixing efficiency nonetheless length of the ramp somewhat act as shape transformer of plume and found good agreement with mixing at 9.75 mm at 2.0 Mach number. Cantilevered ramp injector is also suggested to reduce drag at smallest ramp and swept angle by Wei Huang et al. [2]. Mixing performance and drag force over cantilevered ramp injector has been identified by Wei Huang et al. [25] with the help of numerical simulation. Swept angle, Ramp angle and length of the step was clearly explored and summarized that formation of kidney-shape plume at the nearer location could be affected by the increment in angle of ramp and swept, this gives higher mixing and greater drag force however there was no significance relation seen with length of the step.

E. Swept Micro-Ramp Vortex Generator

Swept ramp fuel injector flow field effect is identified through both numerical and experimental method by James M. Donohue et al. [26]. Separation at the top wall has been clearly seen in the simulation work because of shock wave boundary layer interaction. Laminar based numerical simulation showed better agreement in the recirculation region of ramp base compared with turbulent calculation. Weaker vortices generated by ramp has been observed in contrast experimental, because of numerical viscosity in the vortex core nonetheless maximum injected mole fraction decay rate was found greater in the swept ramp flow field due to strength of the stream wise vortices. Nonintrusive optical diagnostic experimental technique has been used to investigate mixing characteristics over swept ramp by Roy J. Hartfield Jr. et al. [27]. Mixing enhancement due to generation of vortices gave lift the plume in the freestream towards injection wall. Effect of shock was not seen as important parameter for mixing closer to injector. At higher Mach number, mixing rate decrement was seen when vortex structure length increased.

F. Unswept Micro-Ramp Vortex Generator

Planer laser induced iodine fluorescence was used to examine the non-reaction mixing, complex compressible flow performance over unswept ramp fuel injector compared with computational fluid dynamics code by James M. Donohue et al. [28] and Global information of experiment can be

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excessed by CFD simulation with 2% measurement uncertainties.

G.Micro-Ramp Vanes Vortex Generator

Mach reflection control via experimental investigation was done by S. B. Verma and C. Manisankar [29]. Flow separation is commonly induced by Mach reflection, this problem has been alleviated by introducing micro ramp vanes and rectangular micro ramp vanes. Height of the ramp vane is also influenced the stability of Mach reflection interaction, shock wave attachment strength and separation of flow nevertheless Mach stem height can improve effectiveness of control device. Effect of Drag and separation in the flow has been reviewed by H. Holden and H. Babinsky [30] with the help of two type of shock wave boundary layer vortex generators (SBVGs) such as wedge type (Standard micro ramp) and vane type. High shear region was observed in both devices however separation induced by shock wave has been greatly eliminated by SBVGs. Reduction in drag also identified in this review so effective elimination was seen in vane type vortex generator compared with wedge type. Rectangular and triangular micro generator has been chosen to erase flow separation in the flow field with different height examined by P. Martinez-Filgueira et al. [31]. Drag induced by vortex generator was also investigated and concluded that low profile device can reduce the drag. Lowest drag and circulation was obtained due to use of low profile devices. In order to explore the primary vortex, rectangular shape has been chosen and summarized that lower height can control the flow characteristics.

H. Pylon Vortex Generator

Manmohan Vishwakarma and Arvind Vishwakarma [32] briefly explained the effect of pylon to improve mixing and penetration of secondary jet in supersonic flow field through experimental investigation. Penetration height and spread area has been selected to analyzing the pylon effect. Big pylon gave good result compared with small height of pylon geometry however location of secondary jet also gave better effect for spreading and penetration. Improved pressure loss was also rectified by the lower wedge angle.

I. Ramped Vane Vortex Generator

Effect of vortex generators in the supersonic combustor over boundary layer parameters was investigated and explained by S. Lee et al. [33]. Ramped vane vortex generator delivered better vortices compared with ramp and split ramp moreover decreased separation at the center length was also seen. Height and trailing edge length gap showed fully attached flow in the downstream furthermore ramped vane was used as the reduction device for pressure variation and kinetic energy of turbulent flow. Degradation in drag was also found.

III. CONCLUSION

From the above literature review some of the concepts are collected. This data can be used for further research in supersonic flow field.

- Smaller size of the standard micro ramp can control higher momentum deficiency.
- Inflow condition of the combustor plays important role in the field of flow separation.
- Combustion efficiency can be achieved up to 90% with vertical fuel injection.
- Higher Mach number gives stronger vortices.
- Lower equivalence ratio can be used for eliminating shock train in the isolator.
- Distance between counter rotating vortices can help to improve boundary layer separation over dissymmetric micro ramp.
- Back flow elimination can easily vanish by slotted micro ramp, Location and size of slot is also important.
- Cantilever ramp can be used for proper mixing with increment in ramp and swept angle.
- Ramped vane gives better performance towards drag, pressure and separation in boundary layer compared with micro ramp.

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