

Hypersonic Flows Over Multi-Ramp Configurations



Karthik Sundarraj, Ugur Guven, P S Kulkarni, Om Prakash, Ganesh Pawar R

Abstract: The effects of attaching multiple ramps to the standard double ramp configuration along with variations in ramp angle, free-stream Mach number and surface temperature are discussed in this investigation. This study investigates the changes associated with shock wave boundary layer interaction (SWBLI) due to ramp induced flow breakdown and the flow field fluctuation with changes in flow characteristics and design. This type of ramp junctions typically features in re-entry vehicles, engine intakes, system and sub-system junctions, control surfaces, etc. Ramp junctions usually are associated with strong separation bubble that has significant upstream influence impacting the effectiveness of aerodynamic surfaces, engine performance, thermal behavior and stability. Computation studies are carried out using Second order accurate, finite volume RANS solver considering compressible laminar flow characteristics, with solver settings provided like experimental conditions as per literature. Comprehensive double ramp studies with suggestions on reducing the separation bubble size are invariably considered in literature, however there has been no study in understanding the inclusion of additional ramps in such flow scenarios. At the end of this study it was evident that such complex junction needs detailed understanding on how they benefit or impact the overall design of the system. It also gave a very good insight on the nature of flow around such complex junctions and instills motivation for detailed experimental understanding.

Keywords: Multi-ramp, heat flux, hypersonic flows

I. INTRODUCTION

High speed aerodynamics mainly revolves around shocks and shock interactions that change the course of flow field and their behavior. The heat loads and forces are affected due to these alterations. The current technological advancements stand at a stage where the gap between space flight and atmospheric flight are closing in through human interventions and are now a dream that can be realized. The advent of hypersonic vehicle has created hope in this closure of gap and hence a lot of research is conducted in this area. Various researchers [1-10] have investigated shock wave boundary layer and interaction physics through design modifications such as blunting, cavitation, ramping, flaring, external attachments such as aero disc or spike etc.

to evaluate and understand the importance of these design features and also to measure the dependency on these features. The study of interactions between inviscid and viscous regions is called as shock wave and boundary layer interaction and the presence of these interactions in the flow affect both internal and external flow aerodynamics [3]. Generation of separation bubble, boundary layer separation, increased heating and even turbulent re-attachment could be caused through the presence of SWBLI. Careful attention must be given to the design of space vehicle systems and subsystems which experience such SWBLI [3]. As an outcome of design refinement several flow control techniques have been developed to suppress the effects of SWBLI [2]. Hypersonic flow field around blunted cone flare is a very good example that exhibits SWBLI. This example exhibits major features of flow around a space vehicle such as detached bow shock ahead of the cone and oblique shock with boundary layer interaction at the cone flare junction [1]. The SWBLI can produce separated flow at the upstream forward-facing corner where the deflection in the form of a ramp/flare is present. The length of separation has implications for control, stability etc., of a hypersonic reentry vehicle [4]. A separation shock wave is generated due to an abrupt change in flow direction in the presence of ramp. The shock interacts with the boundary layer over the wall which experiences adverse pressure gradient. Flow separation in the presence of such gradients majorly depends on factors associated with flow conditions, geometrical conditions and boundary layer behavior. The parameter at interest is the angle known as incipient separation angle given by Needham and Stollery [6].

$$M_{\infty} \theta_{is} = 80 \sqrt{\bar{X}_L} \quad (1)$$

Where \bar{X}_L is the viscous interaction parameter at ramp junctions;

$$\bar{X}_L = M_{\infty}^3 \sqrt{C} / \sqrt{Re_L} \quad (2)$$

where $C = \frac{\mu_w T_{\infty}}{\mu_{\infty} T_w}$

Boundary layer separation takes place if the incipient separation angle is lesser than deflection angle. Separation occurs at a point ahead of the compression corner, separation leads to compression waves forming a separation shock ahead of the separation region. Separation bubble can be identified by sudden increase in the pressure from nearly constant in the downstream region to a sudden increase in the compression region. The flow reattaches at a point on the ramp surface, the recirculation zone extends between the separation and reattachment point and the distance between these two points is called as length of separation bubble [2].

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In case the ramp angle was smaller than the incipient separation angles the flow would have not undergone much deflection as in the previous case and would have followed a laminar boundary layer profile without separation at the ramp [3]. Such flow alterations occur mainly due to the influence of the ramp on the upstream flow physics. The area of interest shall be the distance between the ramp junction and the upstream point of influence. To enhance the performance of Ramp based SWBLI by reducing the intensity of this interaction through delayed separation several control mechanisms are reported to have been employed, reference to such control mechanisms can be seen in many past investigations. The current research work also pursues the idea of enhancing the performance of any system or subsystem functioning at hypersonic flow regime by altering flow paths through design modifications or study the nature of flow behavior in an unforeseen and unexplored design conditions such as multi-ramps.

Several researchers have investigated shock wave boundary layer phenomenon through several design modifications as stated in earlier sections. R. Savino and D. Paterna [1] conducted validation studies of flow around blunted cone flare in hypersonic flows. Experimental studies were performed in H3 Mach 6 wind tunnel at Von Karman Institute under laminar flow conditions. This work gives a detailed insight on the importance of grid independent study and the influence of mesh size on wall pressure, heat flux and skin friction parameters. It has also been noted through this study that the accuracy of separation bubble size, its location, the flow separation and reattachment locations are all dependent on the resolution of mesh near the wall and at the ramp junction. Sensitivity of wall pressure and heat flux to small changes in surface temperature has also been studied. It has been noticed with increase in surface temperature, the separation bubble length increases. The authors have also considered thermal conductivity effects by considering different materials properties of the experimental model and validating the same through computational methods. Bibin John and Vinayak Kulkarni [2 – 4] have performed wide range of numerical investigations addressing the ramp induced shock wave boundary layer interactions. Extensive and in-depth details on the effect of various flow and geometric parameters and their correlation with the shock wave boundary layer interaction in hypersonic flows performed through finite volume based computational solver are presented. Importance of Quantitative approach over qualitative measurements to estimate the separation bubble length and upstream influence through skin friction and wall shear has been detailed out, which gives a clear insight on the method of approach to understand separation physics [3]. The study also clearly points out the fact that the incipient separation angle concept work well only for well separated flows. It is found from these investigations that the separation bubble length is clearly dependent on flow and design parameters, where with increase in wall temperature the bubble length seems to increase in size and with increase in Mach number the bubble length seems to decrease in size. Strong correlation between leading edge bluntness on separation bubble length has been identified and presented. It is

understood from this investigation the presence of two critical radius of leading-edge bluntness [4].

It is evident from the many literature studies that control of separation bubble is critical to minimize the effects of shock wave interactions in space vehicle systems and sub-systems. It can also be noticed that almost every literature investigation addresses only regions with single and double ramp junctions, but there are almost nil investigations related to multi-ramp junctions which also gets featured in such hypersonic vehicle component and system designs. Multi-ramp junctions also pose severe design challenges and it is necessary to take conscious efforts while designing space vehicles. While these previous research works provide very good insights on the SWBLI by varying ramp angles, leading edge bluntness, freestream velocity etc., which becomes the core basis of the current work, the present research work focuses on the study of shock wave and boundary layer interactions with triple ramp and quad ramp configurations, considering the basic understanding of flow physics around single and double ramp configurations. This way it also helps in understanding the effects of having a multiple ramp on the upstream separation bubble already present at the second ramp junction along with the understanding of how the presence of additional downstream ramps overall changes the shock structure and flow. Computational investigations are carried out to study and understand the behavior of ramp induced shock wave and boundary layer interactions for three and four ramp configurations, wherein the first two ramps are considered as specified by R. Savino and D. Paterna [1], while the third and fourth ramp angles are varied in combination along with variations in freestream and surface temperature, to study the effects on the separation bubble length at all three ramp junctions. Since the studies presented by Bibin John and Vinayak Kulkarni [3] address in detail the relation between flow conditions and design variations on separation bubble size, it becomes a key consideration to test these correlations on multi-ramp configurations and to assess if these variations still continues to be an effective technique to understand and predict separation and hence the current research work considers triple ramp angles of 7.5° , 10° , 12.5° and 15° , with same angles considered for fourth ramp along with a blunt radius of 3.5mm. All combinations of ramp angle variations between third and fourth ramps are considered for this simulation study. The freestream Mach number is varied between 6 to 8 and the surface temperatures as 270K, 300K and 330K. Simulation tool validation is performed using the base geometry and boundary conditions as provided by R. Savino [1] in their computational and experimental validation studies. Post successful validation, efforts are taken to initially study the effect of adding multiple ramp junctions to the base geometry on the shock wave boundary layer interaction, followed by considering variations in freestream Mach number and surface temperatures in the presence of third and fourth ramp. Details on the solution methodology, model and discretization details are presented in the next section.

Discussions on the findings of adding multiple ramp junctions in association with freestream variations, thermal variation and its implications on the separation bubble is discussed in Section III, followed by conclusions and future works in Section IV.

II. COMPUTATION METHODOLOGY

The numerical investigations are carried out using High Resolution Flow Solver on Unstructured meshes (HiFUN), considering it to be compressible laminar flow solver. Following conservation equations for mass and momentum are considered in the solver algorithm,

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial (f_i + f_v)}{\partial x} + \frac{\partial (g_i + g_v)}{\partial y} = \mathbf{0} \quad (3)$$

Where,

$$\mathbf{U} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{bmatrix} \quad f_i = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ \rho uH \end{bmatrix} \quad g_i = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ \rho vH \end{bmatrix}$$

And,

$$f_v = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ u\tau_{xx} + v\tau_{xy} - q_x \end{bmatrix} \quad g_v = \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \\ u\tau_{xy} + v\tau_{yy} - q_y \end{bmatrix} \quad (4)$$

Here, \mathbf{U} is the vector of conserved variables, f_i and g_i are inviscid flux vectors along x and y directions respectively. Also f_v and g_v are viscous flux vectors along x and y respectively,

The expressions for the viscous stress and heat conduction terms are given below:

$$\tau_{xx} = \frac{\mu}{Re_\infty} \left(\frac{4}{3} \frac{\partial u}{\partial x} - \frac{2}{3} \frac{\partial v}{\partial y} \right), \quad \tau_{yy} = \frac{\mu}{Re_\infty} \left(\frac{4}{3} \frac{\partial v}{\partial y} - \frac{2}{3} \frac{\partial u}{\partial x} \right)$$

$$\tau_{xy} = \frac{\mu}{Re_\infty} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)$$

$$q_x = \frac{\mu}{M_\infty^2 Pr_\infty Re_\infty (\gamma - 1)} \frac{\partial T}{\partial x}$$

$$q_y = \frac{\mu}{M_\infty^2 Pr_\infty Re_\infty (\gamma - 1)} \frac{\partial T}{\partial y}$$

For the present study, fluid is assumed to be as ideal gas. HLLC flux [11, 12] is adopted for inviscid flux scheme and Green Gauss [13] for viscous flux scheme with a special accuracy of 1. Implicit time integration approach is used for obtaining numerical approximation of the solution, with the relaxation fraction of 0.4 and the permissible range of CFL (Courant-Friedrichs-Lewy) [19, 20] number is 0.09 – 1.

$$\frac{\mu}{\mu_{ref}} = \left(\frac{T}{T_{ref}} \right)^{\frac{3}{2}} \left(\frac{T_{ref} + S}{T + T_\infty} \right) \quad (5)$$

Laminar viscosity (μ) is computed by using Sutherland's law [18], where the Sutherland's constant (S) for air is considered as (110.56), the reference viscosity (μ_{ref}) is ($17.16 \times 10^{-6} \text{ N s/m}^2$) of air at a reference temperature (T_{ref}) of (273.15 K), t , while the Prandtl number (Pr) is assumed to be 0.74.

III. NUMERICAL INVESTIGATIONS

Inter-code comparison, grid dependency study and theoretical validation stagnation pressure and post shock temperature are performed on the model and boundary conditions as considered by R. Savino [1]. The base model considered for initial validation studies is henceforth referred as double ramp, which is 159.11 mm in total length, with first ramp angle 7.5° , second ramp angle 10° and a leading-edge bluntness of radii 3.5 mm. A third and fourth ramps of length 62.5 mm and 53.5 mm are attached to the base double ramp model, for the current investigation on ramp induced shock wave boundary layer interactions. Model details along with the computation domain and boundary conditions are shown in Fig. 1 & 2. The freestream conditions and the details about both the ramp angles are mentioned in Table-I. Multi-block structured meshing has been performed to discretise the computation domain. Different mesh combinations with variations in mesh spacing both in normal and along the body are considered, the detailed of the same is shown in Table-II, a sample grid used throughout this investigation is shown in Fig. 3. Due to availability of multiple computation tools, inter-code comparison was necessary to ensure the chosen tool is the best to capture the flow physics that involves, laminar high-speed flows with high gradient flow separations along with the formation of shocks. The pressure distribution along the double ramp model [1] was taken as a standard to perform the inter-code comparison. HiFUN proved to predict the experimental results very accurately and for this reason it has been chosen for all simulations in this investigation. Through grid independence study it was found that the mesh parameters used by R. Savino [1] was not suitable for HiFUN to match the experimental data. Grid spacing normal to the model was found as the major criterion to reach solver accuracy, while maintaining the overall mesh count same as in literature. It was found from grid independence study that the mesh size of 960 x 160 and 480 x 80 with 30micron normal mesh spacing had excellent agreement with experimental surface pressure values as shown in Fig. 3a. The separation and reattachment points have very good match while there is slight but acceptable computational underprediction in the post attachment zone. It can be noticed that 480 x 80 captures the bubble region better, but the post reattachment region is extremely critical for multi-ramp studies as it involves reattachment shocks and shear region which is captured better by 960 x 160 grid. Quantitative parameters such as surface heat flux was also validated, represented in Fig. 3b. As can be seen, there is underprediction of the separation point and a higher heat flux prediction post reattachment when compared to the experimental data. As indicated in the findings by R. Savino et. al [1], there are noticeable changes in bubble length and heat flux with time during an experimental study. The surface temperature increases with time while conducting a high-speed flow experimentation study. There is delay associated with data acquisition during which time the surface temperature increases by almost 10%.

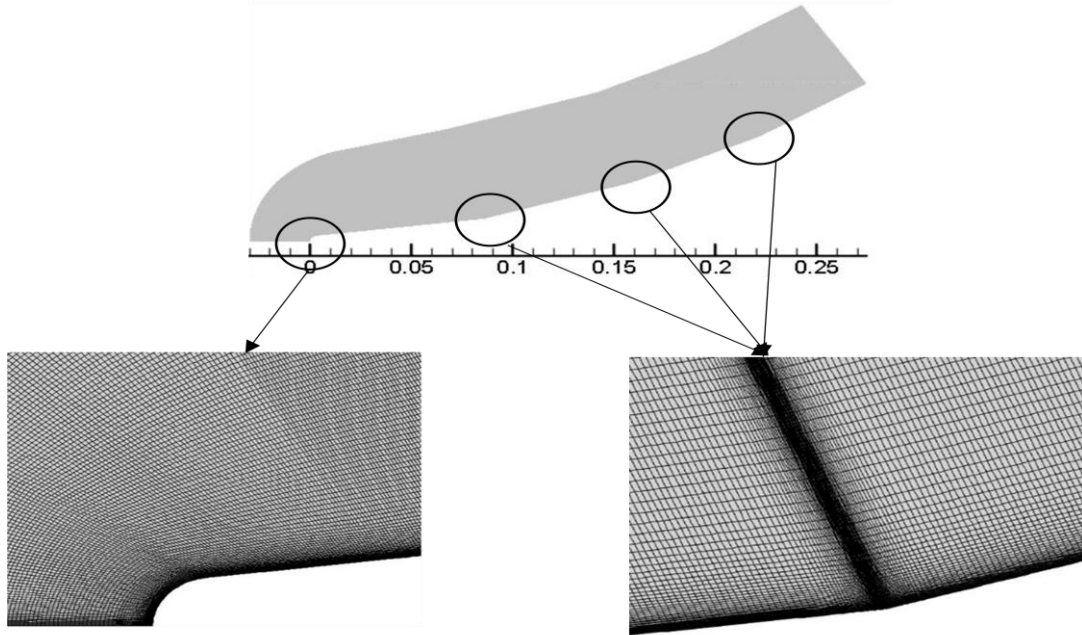


Fig. 3. Sample grid used for quad ramp configuration

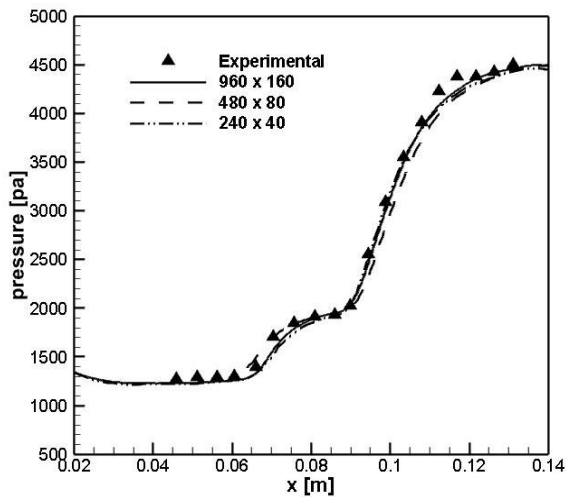


Fig. 3a. Grid independence study of surface pressure profile over double ramp

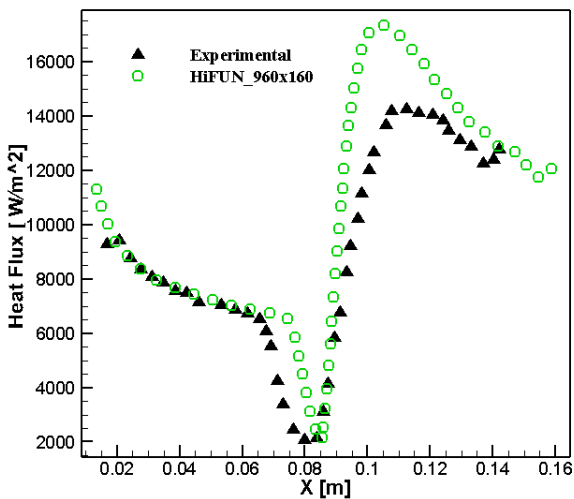


Fig. 3b. Grid independence study of surface heat flux profile over double ramp

which underpredicts the separation point and the surface heat flux is higher than the experimental value. The experimental values show the exact trend of predicting a bigger separation bubble and a reduced surface heat flux, indicating a possible delay in data acquisition. There are also chances of non-uniform flows in the test section resulting in boundary layer excitation causing early separation and lower heat flux due to turbulent convection. From the double ramp validation, it was found that 960 x 160 was the most reliable mesh for all design variations and hence the same mesh sizing was continued for the multi-ramp configurations having third and fourth ramps by adding equal mesh divisions of 400 elements on each ramp making it 1320 x 160 on triple ramp configuration and 1720 x 160 on quad ramp configuration, any lesser mesh count was unable to capture separation and reattachment points accurately on downstream ramp junctions. The following sub-sections shall discuss on the effect of varying free-stream Mach number on triple and quad ramp configurations, the effect of changing surface temperatures on the separation bubble length and surface heat flux and the study on combined ramp angle variations between third and fourth ramps on shock wave boundary layer interaction.

IV. TRIPLE RAMP CONFIGURATION

A. Combined effects of varying free-stream Mach number and ramp angle

From the investigations done by Bibin John et. al. [3], it is evident that variation in ramp angle has a direct connect with freestream Mach number, the incipient separation angle decreases with an increase in freestream flow velocity (Mach). The study also reveals the fact that increasing ramp angle increases the bubble length and increasing the freestream Mach number reduced the length of bubble.

The current study details out the combined effects of varying the free-stream Mach number and ramp angles to understand the changes in flow field and the shock wave boundary layer interactions. The base model or a double ramp configuration with first ramp angle of 7.5° and second ramp angle of 10° [1] is considered. To this base model a third ramp with varying angles as mentioned in Table-I is attached. Freestream Mach number is varied over all third ramp conditions to understand the changes in surface pressure distribution, skin friction coefficient and the separation bubble length. The surface pressure distributions are presented from Fig. 4 (a-d) and the skin friction coefficients are presented from Fig. 5 (a-d). From the plots it is evident that the flows are fully separated at both the ramp junctions and hence the deflection angles are above the incipient separation angle as described in the literature. Interestingly it is noticed that the correlation between Mach number and bubble size seems to not follow the trend as mentioned in earlier studies. Ideally the separation bubble length must be smaller for higher Mach numbers as per earlier findings, but from the pressure distribution plots, Fig. 4a to 4d, it is evident that this correlation no more is valid for configurations above double ramps. The correlation has been reversed in the case of triple ramp configurations wherein the separation point and reattachment points have been pushed upstream and downstream respectively in case of higher Mach number, while the separation point has moved downstream, and reattachment point upstream in case of lower Mach number. This trend remains same for all third ramp angles with increase in freestream Mach conditions, this could be attributed to the upstream influence of the presence of a third ramp junction. Quantitative understanding through skin friction coefficient gives even better insights on separation and reattachment behavior in the presence of a third ramp. From Fig. 5 (a-d) it is interesting to notice that the size of the separation bubble is bigger for higher Mach numbers at the first junction while the separation bubble size is smaller for higher Mach numbers at the second junction. This is unique as two different correlations between Mach number and bubble size can be noticed at the same time, wherein the correlation is following inverse trends at the first junction while it follows the typical trend at the second junction as compared to the study by Bibin John et. al [3]. This is indicative of a significant downstream effect of having a third ramp on the flow physics. The separation point at the first junction moves downstream with increase in third ramp angles. The downstream effects are primarily due to changes in boundary layer caused by the compression corner at the second junction. What can also be noticed is that the reattachment shocks are becoming weaker at the first junction with increase in third ramp angle which are resulting in upstream shift in separation points at the second junction leading to increase in bubble size for lower Mach and reduction in bubble size for higher Mach. This is attributed to the reduction in inertia of the flow, where the lower Mach flows tends to become slower at the second junction resulting in early separation, while the higher Mach flows are still faster at the second junction resulting in later separation and so reduced bubble length. The skin friction peaks that can be noticed in the plots are indicative of a turbulent reattachment shock that also leads to a highly turbulent post shock shear region which are indicated as fluctuations post the reattachment point at the second

junction. Table-III reassures that the presence of third ramp has effects on the length of the separation bubble located at the first junction. The table compares size of separation bubble between double ramp and triple ramp configurations. As can be seen the biggest bubble corresponds to the double ramp measuring 36.8 mm while all other bubble sizes corresponding to triple ramp are smaller indicating an upstream influence. The upstream influence could be because of the thickening of the boundary layer due to the compression corner at second junction. The entropy layer might be engulfed inside the boundary layer leading to the increase of separation bubble size at the first junction. Completely engulfed entropy layer alters the flow properties which is assumed to affect the separation and reattachment points at the first junction. It is critical to understand this flow physics in detail which is identified to occur in situations where there could be a complex junction in a system or a subsystem of high speed vehicles and so experimentation must be considered as the next step for better understanding of such complex flow physics and also to add basis for all the computational investigations.

B. Wall temperature effects at different Mach numbers

It is evident from the investigations done by R. Savino [1] and Bibin John [3] that variations in surface temperature has significant effect on the shock wave boundary layer interaction, hence it is important to study this parametric change on triple ramp configuration as well, to understand whether the correlation still follows the same trend for multi-ramp junctions. For this study triple ramp configuration with 7.5° third ramp angle is considered as it exhibits fully separated flow at both ramps with lowest pressure peaks at second junction. Freestream Mach number chosen as between 6 to 8 and surface temperatures considered are 270 K, 300 K and 330 K. Surface heat flux for different Freestream Mach numbers are shown in Fig. 6-8 and the surface pressure distribution for Mach 6 is shown in Fig. 9. Simulation with adiabatic wall condition is also considered and plotted along with the isothermal wall boundary, to understand the upstream influence on the flow physics with these different wall thermal treatments. Table-IV gives a detailed perspective on the effects of bubble sizes due to the variations in freestream Mach number in combination with varying surface temperature. It can be understood from this study that there is a definite upstream influence with increase in wall temperature. This influence is seen throughout the configuration at all locations and the presence of third ramp

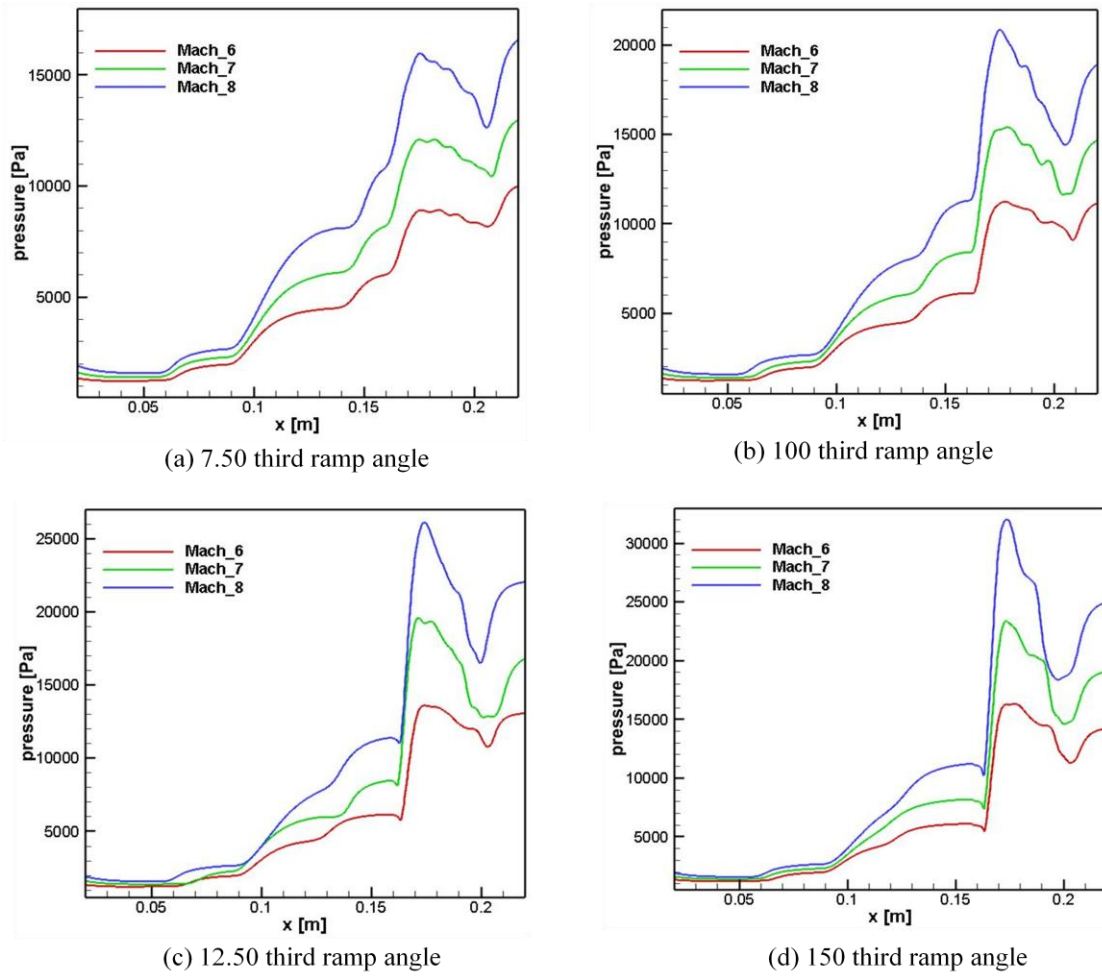


Fig. 4. Surface pressure distributions of triple ramp configurations at different Mach numbers

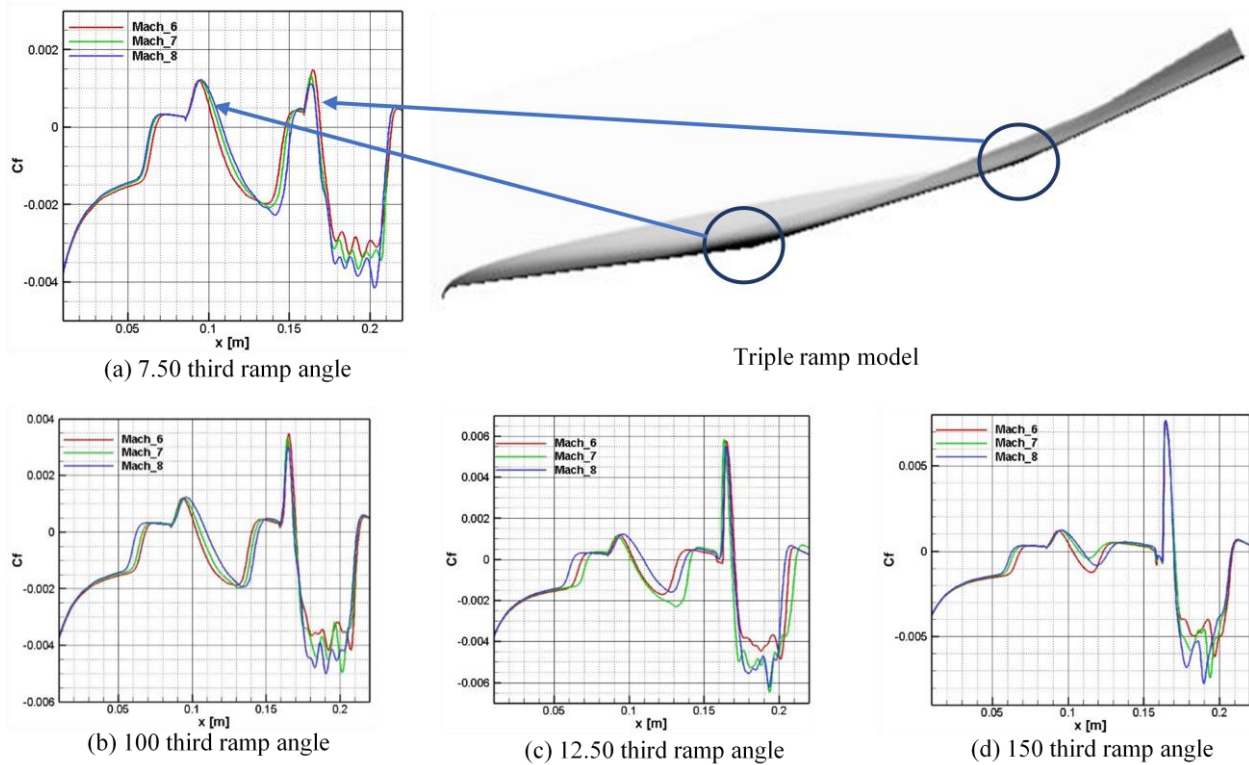


Fig. 5. Skin friction coefficients of triple ramp configurations at different Mach numbers

Table-III: Summary of separation bubble sizes for varying freestream Mach numbers and ramp angles

M_∞	Configuration	α	Bubble	L_b
6	DR		FB	36.8
	TR	7.5	FB	36.47
			SB	21.6
	TR	10	FB	34.87
			SB	29.94
	TR	12.5	FB	34.47
SB			7.88	
TR	15	FB	34.6	
		SB	12.95	
8	DR		FB	31.72
	TR	7.5	FB	44.31
			SB	15.92
	TR	10	FB	47.2
			SB	24.06
	TR	12.5	FB	46.8
SB			31.95	
TR	15	FB	46.3	
		SB	11.83	

DR = double ramp, TR = triple ramp, α = third ramp angle, FB = first bubble, SB = second bubble, L_b = bubble length

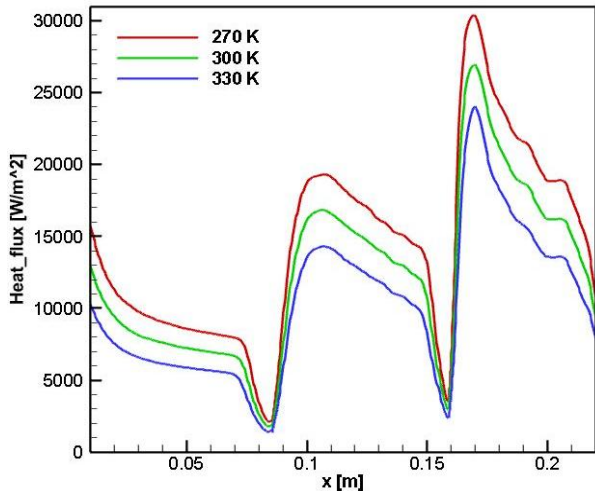


Fig. 6. Wall temperature effects on surface heat flux distribution at Mach 6

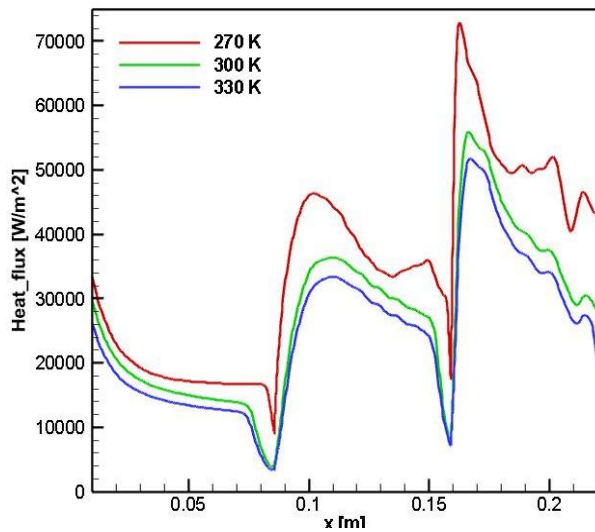


Fig. 7. Wall temperature effects on surface heat flux distribution at Mach 7

does not alter the correlation between surface heat flux and SWBLI. It is interesting to observe from the heat flux plots that the combined study of freestream Mach number, surface temperature and the third ramp has major upstream influences and has noticeable increase in peak pressure values post reattachment at both the junctions. The increase in peak pressure values are mainly attributed to smaller but stronger separation bubbles at higher freestream Mach which causes stronger compression corner shocks and a much stronger reattachment shock followed by highly turbulent shear zone. Increase in surface temperature causes rise in viscosity properties of the flow which causes an increase in the boundary layer thickness. Thicker boundary layer reduces heat flux while also causes early separation as can be seen in Table-IV. It is also noticed that the separation point is moved downstream with increase in freestream Mach number at both ramp junction while still early separation is noticed with increased wall temperature. It can be deduced that increase in Mach number does reduce the bubble length at both junctions while bubble length remains to be bigger for higher wall temperatures. Biggest separation bubble of size 36.47 mm and 21.6 mm at the first and second junctions respectively can be seen for Adiabatic wall condition at Mach 6 indicating the effects of surface temperature on boundary layer thickness. The bubble size continues to increase at the first junction in case of adiabatic conditions with bubble size reaching a maximum of 44.31 mm at first junction for Mach 8 while the maximum bubble size in case of isothermal surface temperature of 330 K at Mach 8 freestream condition in just 14.31 mm. This is a considerable reduction in bubble size noticed due to surface temperature changes. Hence it is evident that increase in freestream velocity with increase in wall temperature reduces the bubble size considerably while also reducing the heat flux,



on the contrary considering adiabatic wall conditions with increase in freestream Mach number has adverse bubble growth at the first junction.

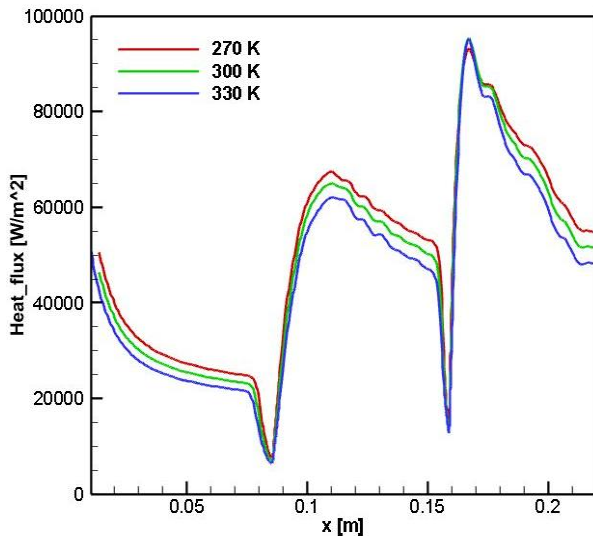


Fig. 8. Wall temperature effects on surface heat flux distribution at Mach 8

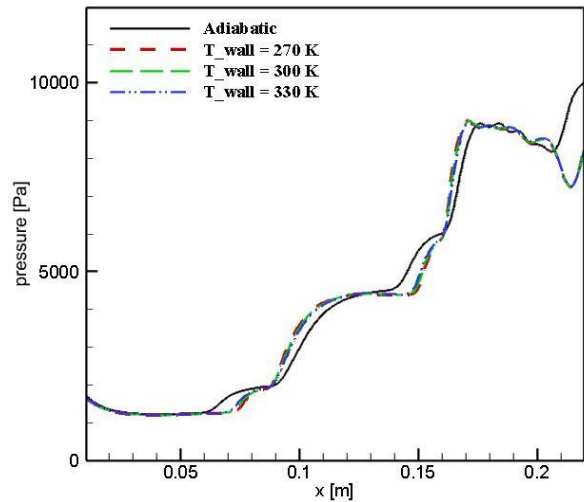


Fig. 9. Wall temperature effects on pressure distribution at Mach 6

Table-IV: Summary on effects of bubble sizes due to the variations in freestream Mach number and surface temperature

M_∞	T_W (K)	FB			SB		
		X_{sep} (mm)	X_{re} (mm)	L_b (mm)	X_{sep} (mm)	X_{re} (mm)	L_b (mm)
6	Adiabatic	67.31	103.78	36.47	147.6	169.2	21.6
7	Adiabatic	65.01	106.58	41.57	149.2	167.5	18.3
8	Adiabatic	64.27	108.59	44.31	151.38	167.3	15.92
6	270	77.15	94.7	17.54	153.4	163.98	10.58
7	270	84.07	88.01	3.93	158.4	159.9	1.5
6	300	75.94	95.79	19.84	152.8	164.5	11.7
7	300	78.31	94.3	15.99	154.92	162.5	7.58
6	330	74.76	96.96	22.20	152.1	165.28	13.18
7	330	77.27	95.4	18.12	154.55	162.8	8.25
8	330	79.45	93.76	14.31	156.4	162.3	5.9

M_∞ = freestream Mach, X_{sep} = separation point, X_{re} = reattachment point, L_b = bubble length, T_W = wall temperature

V. QUAD-RAMP CONFIGURATION

A. Effects of varying freestream Mach number and ramp angle

From earlier investigations, it is evident that multi-ramp design configurations have significant effects in the flow physics leading to changes in correlations between freestream and design modifications. It is also certain that the flow around such complex multi-junction configurations have some of the most complex flow structure and shock interactions and must not be studied in detail. These multi-ramp junctions also change the understandings derived from earlier research findings of Bibin John et. al [3] where the correlation between freestream Mach number and bubble length vary with increase in ramp junction as noticed in the earlier section. Numerical simulations are carried out to study the effects of adding a fourth ramp to the earlier considered three ramp configurations on the flow physics associated with shock wave boundary layer interaction. The first and second ramp are the same as base model, the third

ramp is fixed at 7.5° ramp angle. To this triple ramp configuration, a fourth ramp is attached making it a Quad-ramp configuration. Fourth ramp angles are varied between 5° to 12.5° with a varying freestream Mach number between 6 to 8 and the associated effects on skin friction coefficient and surface pressure distributions are shown in Fig. 10 (a-d) and Fig. 11. (a-d) respectively. A minimum ramp angle of 5° is considered for the fourth ramp as it is critical to test the validity of incipient separation angle. It is evident from the pressure distribution plots that the incipient separation theory by Bibin John et. al [3] still holds, where the separation bubble for 5° ramp angles is almost negligible in size indicating that it is not a fully separated flow whereas, the bubble sizes increase with higher ramp angles beyond 7.5° as per earlier studies. From the skin friction coefficient plots, the trends upto the second junction is exactly as depicted in triple ramp configuration,

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where the bubble size is larger for higher freestream Mach at first junction and the bubble size is least for lower freestream Mach. At the third junction the separation and reattachment points do not show noticeable variations with increase in freestream Mach number, indicating that the separation bubble size at the third junction is no more dependent on the freestream velocity conditions. This could

attribute to low inertia by the time the flow reaches the third junction across all Mach conditions. It is also noticed across all ramp variations that the region after the reattachment at the second junction is highly turbulent due to a turbulent reattachment causing a highly turbulent shear region, the effects of the turbulent shear and the shock follows

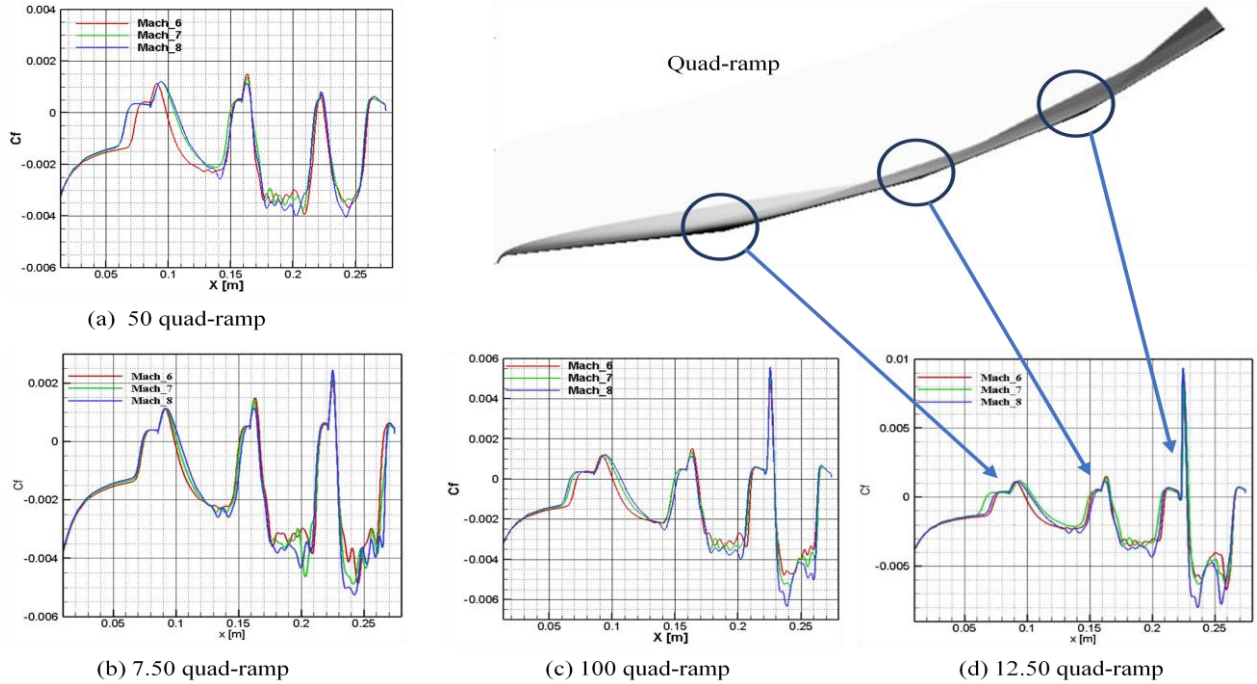


Fig. 10. Skin friction coefficients of quad-ramp configurations at different Mach numbers

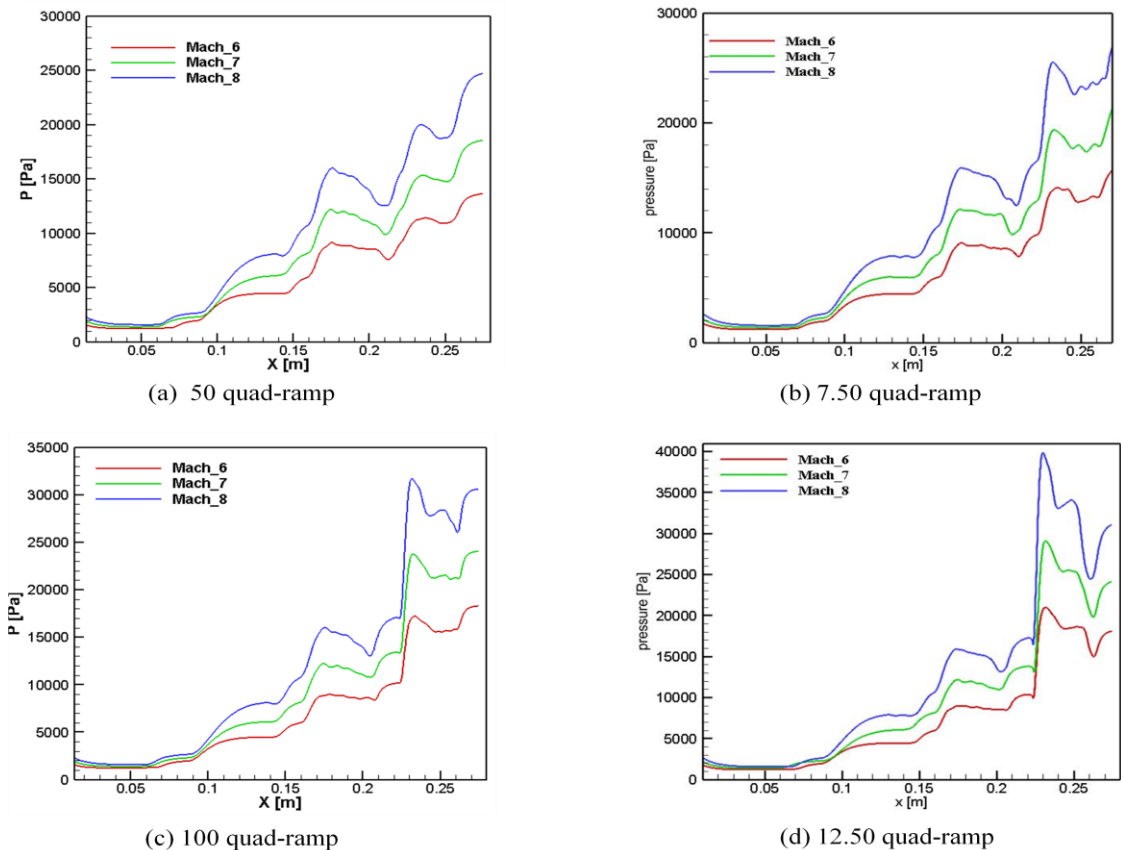


Fig. 11. Surface pressure distributions of quad-ramp configurations at different Mach numbers

downstream towards the third junction increasing the intensity of reattachment shock at the third junction. This could be attributed to turbulence dissipation downstream through shear layers causing a stronger corner shock at the third junction. These studies indicate that such complex junctions have very unpredictable flow natures and may not follow every correlation that proves well for a simple double ramp configuration, encouraging the need for detailed and in-depth experimental studies to clearly understand flow physics when design scenarios lead to such complex multi-ramp junctions.

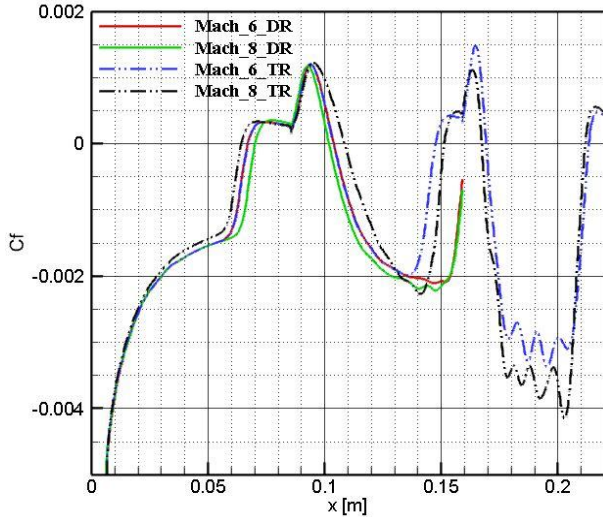


Fig. 12. Separation bubble comparison between double and triple ramp configurations

VI. CONCLUSION

Complex multi-ramp junctions were investigated to study the effects of these design modifications on flow physics followed by a detailed study on how changes in flow conditions and surface properties in combination with design changes the different characteristics of shock wave and boundary layer interactions which includes understanding of separation and reattachment behaviors, shock interactions, shear regions and boundary layer physics. Extensive validation activity was performed to ensure accuracy of flow solver through inter-code comparison and grid independence based on which a common solver and grid was chosen as the outcome of this validation. Two different ramp configurations with complex multi-ramp junctions are considered for flow computation studies, one the triple ramp configuration with two distinct ramp junctions with three ramps and the other a quad-ramp with three ramp junctions with four ramps. These complex design configurations do not feature much in any of the past literatures but poses equal or even higher design challenges due to the complexity in flow patterns. Both qualitative and quantitative methods are employed to understand the overall effects of these design configurations on the shock wave boundary layer interaction. Current study investigates the combined effects of varying the free-stream Mach number and ramp angles to understand the changes in flow field for both the configurations. The most crucial finding is that such complex junctions have very unpredictable flow natures and may not follow every correlation that proves well for a simple ramp junction. One such correlation that

seems to fail is the behavior of bubble length with increasing freestream Mach number. It has been found that with increase in ramp junctions, the bubble at the first junction increases with increase in freestream Mach number which is an inverse correlation when compared to literature studies, while the bubble length decreases in size with higher freestream Mach numbers at the second junction. The bubble length at third junction seems to no more change its characteristics with increase in freestream Mach number with almost same separation and reattachment points. The effect on the first junction is mainly attributed to the upstream influence of the presence of multiple ramps, causing the boundary layer to thicken. The entropy layer might be engulfed inside the boundary layer leading to the increase of separation bubble size at the first junction. Loss of inertia causes the bubble size to increase at higher ramp junctions for lower Mach numbers eventually becoming almost constant size for all Mach numbers at third junction. The bubble behavior on a double ramp junction follows the correlation of smaller bubble length at higher Mach number whereas the reverse is seen when there are additional ramps, this is evident and seen in the Fig. 12. The bubble lengths can also be referred to in Table-III, where same trends are noticed. These multi-ramp configurations also exhibit highly turbulent reattachment shocks and turbulent shear regions making it evident that laminar considerations will not be the right method, while reliable understanding on physics can be achieved and yet will require turbulent computational studies to derive at more accurate inference. Wall temperature variation and its effects on shock wave boundary layer interactions are also studied in this investigation. Simulation with adiabatic wall condition is also considered and plotted along with the isothermal wall boundary, to understand the upstream influence on the flow physics with these different wall thermal treatments. It can be understood from this study that there is a definite upstream influence with increase in wall temperature. From the investigation in can be deduced that increase in Mach number does reduce the bubble length at both junctions while bubble length remains to be bigger for higher wall temperatures. Adiabatic wall condition is found to have the biggest bubble size, this mainly is found to happen because increase in temperature increases the boundary layer thickness and hence early separation. These studies indicate that such complex junctions have very unpredictable flow natures and may not follow every correlation that proves well for a simple double ramp configuration, encouraging the need for detailed and in-depth experimental studies to clearly understand flow physics when design scenarios lead to such complex multi-ramp junctions. Future studies will investigate such multi-ramp configurations in detail through experimental methods where detailed insights can be arrived at with respect to multi-ramp configurations and their effects on shock wave boundary layer interactions.

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