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Relocation of the Double-Bump on the Ramp of a Supersonic Air-Intake for its Improved Performance

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ABSTRACT

The performance of a supersonic air-intake is important for efficient combustion in an air-breathing engine. Recent literature shows a study of the design of a supersonic air-intake, with bumps located on its ramp surface. The bumps generate oblique shocks which should result in a pressure jump downstream of the shocks. This would result in compressed and decelerated flow at the exit of the intake, for efficient combustion downstream. However, some recent studies found that a double-bump degrades the performance of the air-intake compared to a single bump. This sounds counter-intuitive. In this work, this problem is investigated and an improved location for the double-bump is proposed based on the physics of high-speed gas dynamics. Computational analysis is then done to analyze the performance of the supersonic air-intake with an incoming freestream flow of Mach 2.2, using CFD package ANSYS Fluent. The computational methodology is first validated using results of surface pressure distribution on the wall of the intake, for a standard test case available in literature. The methodology is then applied for the supersonic air-intake with the proposed location of the double-bump. The resulting Mach contours and pressure contours are discussed in relation to the compression and Mach number obtained at the exit of the intake. The results show that with the location proposed in this work, the double-bump results in a system of shocks and reflected shocks which are contained well within the air-intake. This results in higher pressure recovery and lower Mach number at the exit of the intake, compared to a single-bump intake. As the air with higher static pressure and lower speed enters the combustion chamber downstream, both these favourable features should help in more efficient combustion.

1. Introduction

The supersonic air-intake is a vital component of an air-breathing propulsion system's performance. Supersonic air-intake is used to slow down the flow from supersonic to subsonic speeds, delivering a matched air mass flow rate to the engine and reducing performance losses, with the help of a correct shock system and subsonic diffuser. The layout and flow physics in a general supersonic air-intake are shown in Figure 1.

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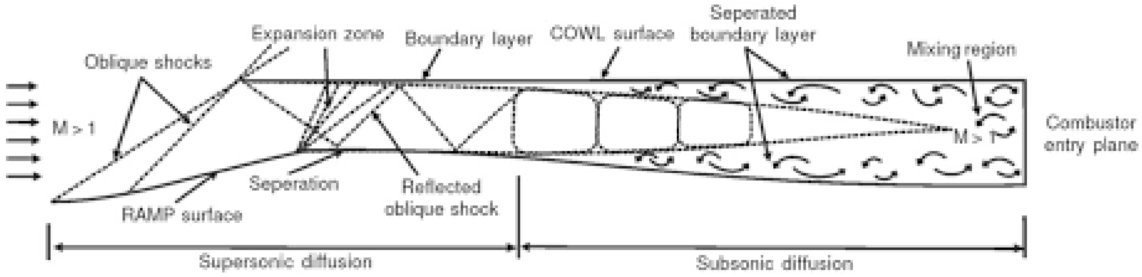

Fig. 1. Schematic of flow field in a general supersonic air-intake [1]

There are many designs of air-intakes in use depending on the application as discussed by Kurth and Bauer [2]. The complex flow features inside a supersonic air-intake are discussed by Saunders and Keith [3]. Slater [4] demonstrated that Computational Fluid Dynamics (CFD) can be used as a high-fidelity tool to analyze such flows.

A supersonic air-intake with a bump on its ramp is known as a Diverter-less Supersonic Inlet (DSI). These intakes are light in weight and have a relatively less complex structure. Extensive research has been carried out [5-12] on DSI-type intakes.

Dhanlobhe *et al.,* [13] investigated the effect of placing a double-bump vis-a-vis a single bump on the ramp of a supersonic intake, towards achieving higher pressure recovery at the exit. Surprisingly, the double-bump resulted in lower pressure recovery. This is counter-intuitive. In this study, this problem is investigated and an improved location for the double-bump is proposed based on the physics of high-speed gas dynamics. We then perform computational analysis of the flow field that develops in the supersonic inlet (a) with the double-bump configuration of Dhanlobhe *et al.,* [13] and (b) the arrangement of double-bump proposed in this paper. The performance of a supersonic air-intake is evaluated based on the pressure recovery and Mach number achieved at the exit of the intake. Since the air at the exit of the intake participates in combustion, higher static pressure and lower Mach number are the desired objectives.

2. Formulation of the New Location of the Double-Bump

The basic geometrical features of a supersonic intake referred to in this work are shown in Figure 2. Many researchers studied the performance of a supersonic air-intake by placing a single bump on one of the ramps of the intake. Dhanlobhe *et al.,* [13] tried to improve the performance of such an intake by instead placing two bumps on the ramp surface. It was argued that the additional bump would produce an additional oblique shock which should add to the compression of air and result in better pressure recovery.

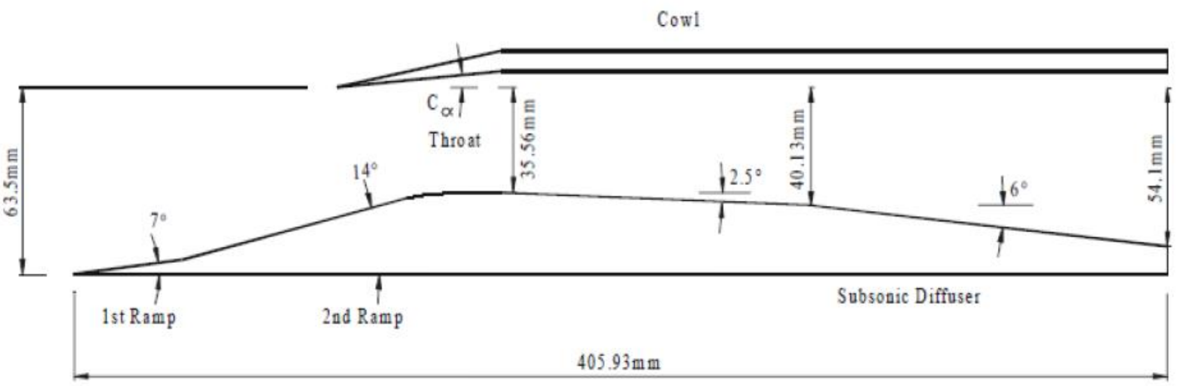

Fig. 2. Schematic design of a supersonic air-intake [14]

However, the results of Dhanlobhe *et al.,* [13] showed that the double-bump configuration produced lower pressure recovery. This is counter-intuitive. We closely studied the configuration of the double-bump used by Dhanlobhe *et al.,* [13]. In their work, they modified the supersonic air-intake design of Das and Prasad [14] shown in Figure 2, by introducing a bump on the incline of the 1st ramp (refer to Figure 2), and introducing a second bump on the inclined surface of the 2nd ramp. Since the bump on the 1st ramp is far upstream of the cowl lip (see Figure 2), the oblique shock that forms at this bump does not get bounced off the cowling surface and does not yield a system of reflected shocks inside the intake. Hence the contribution of the oblique shock from the first bump (on the 1st ramp), to the increase in static pressure of air entering the intake, is low. In this study, we propose that the first bump also should be located on the 2nd ramp, pushing it inwards of the intake. This should result in the oblique shock at this bump getting reflected at the cowling wall. The present proposed design and the earlier designs with no bump, single bump, the double-bump used by Dhanlobhe *et al.,* [13] are schematically illustrated below in Figure 3.

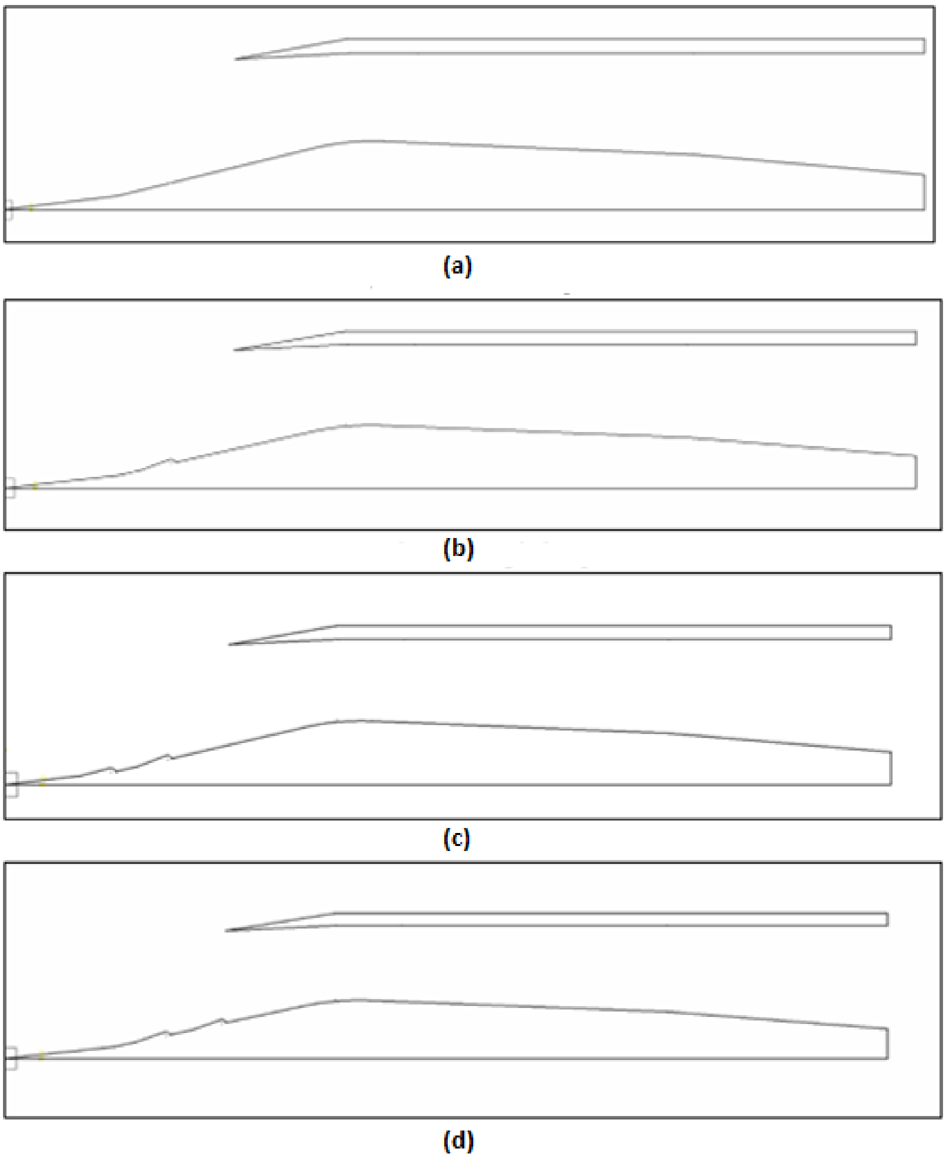

Fig. 3. Intake geometries (a) No bumps on both ramps (b) Single bump on 2nd Ramp (c) Double-bump configuration used by Dhanlobhe *et al.*, [13] (d) Double-bump configuration proposed in the present work

3. Methodology

3.1 Computational Flow Analysis of the Supersonic Air-intakes

The flow-fields in the four supersonic air-intake configurations are obtained using ANSYS Fluent® software. The computational methodology used in this work is first validated with the results reported by Das *et.al.*,[14] for the case of no bump on the ramp, specifically where the cowl deflection angle (refer to Figure 2) is $C_\alpha = 1^o$.

3.2 Validation of Computational Methodology

The simulations are carried out for the corresponding freestream Mach number M = 2.2. A two-dimensional steady-state, density-based flow solver is used. To determine a suitable mesh size, a grid-independence study is performed with four different meshing sizes: Very coarse (53000 cells), Coarse (81800 cells), Medium (97900 cells), and Fine (121200 cells). Figure 4 shows the plotted results of the Grid Independence test. A grid has minimum spacing near the wall in the y-direction which is 0.08 (wall Y+ value is 0.08).

Based on the agreement of results with the reference by Das *et.al.*,[14], the structured grid with 97000 nodes (Medium meshing) is adopted for meshing for all the supersonic intake designs in this study.

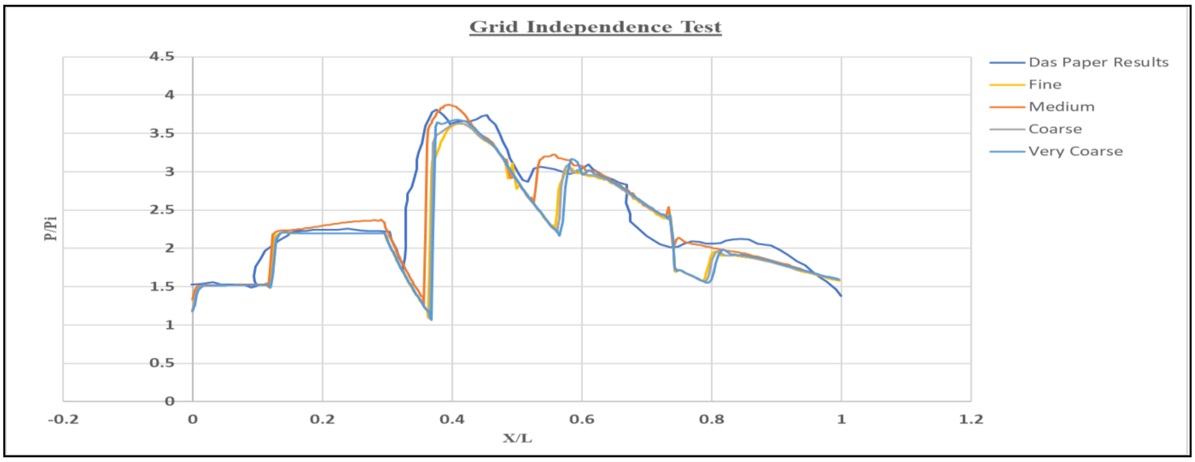

Fig. 4. Grid independence test

The comparison of the static pressure distribution over the ramp surface obtained in this work, with results from [14], is shown in Figure 5. There is a reasonably good agreement between the two sets of results. Hence this computational methodology is adopted for the present study.

3.3 Mesh Generation

For the study, the bump with dimensions as shown in Figure 2 is adopted for the four cases - with no bump, with a single bump, with a double-bump of [13], and with a double-bump proposed in this work. The two bumps are installed 10 mm apart from one another.

Figure 6 shows the grid for all the four cases. The fine grid has been adopted near the surface of the intake. The outlet is defined as a pressure outlet while the remaining three boundaries are defined as pressure far-field as in [13]. The ramp surface and the cowl are naturally defined as wall boundary conditions.

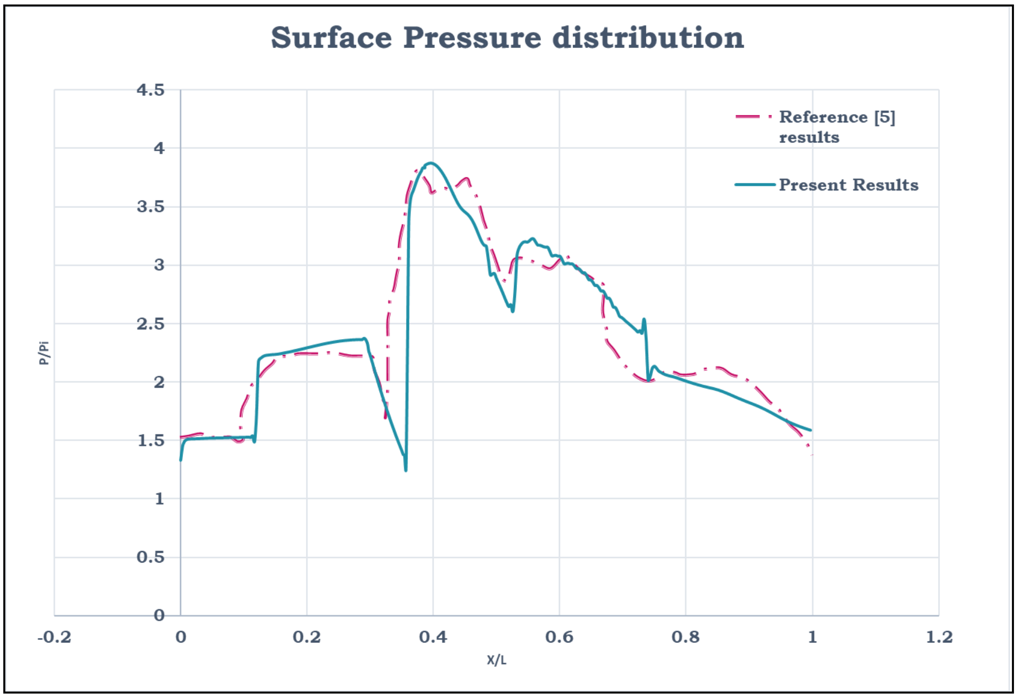

Fig. 5. Surface pressure distribution over ramp surface

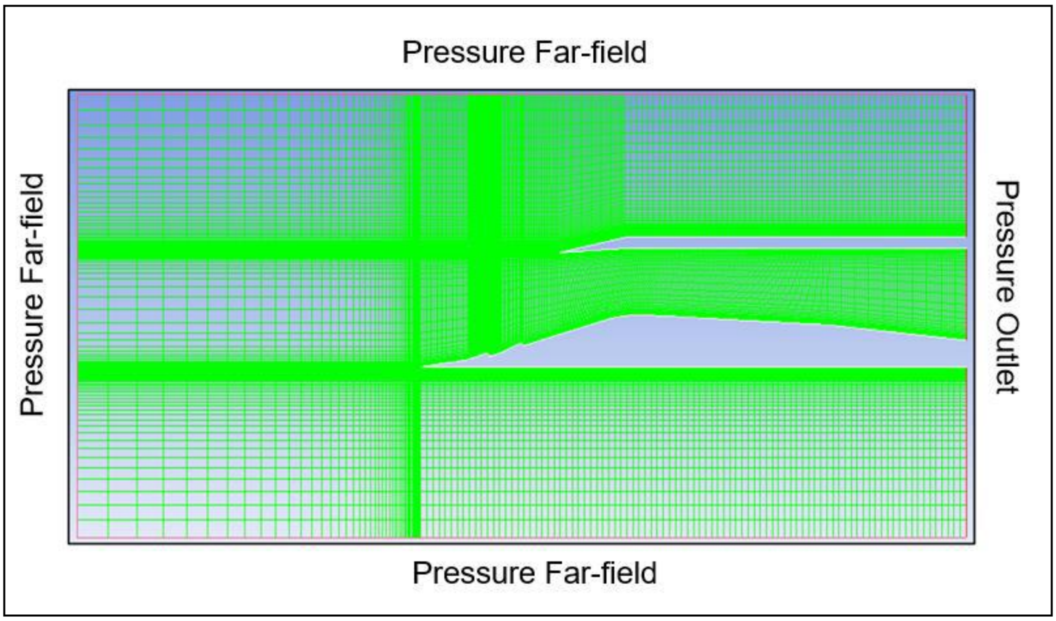

Fig. 6. Computational domain and boundary conditions

3.4 Computational Setup and Methodology

The calculations have been made utilizing the standard k-ω turbulence model which is suitable for internal flows [15]. The material utilized is air, with the property set to the ideal gas. An explicit coupled solver with spatial discretization and a Green Gauss cell-based with a second-order upwind discretization scheme for the flow and transport equations were used for the computations.

The important setup conditions for the computations are listed in Table 1.

Table 1
Computational Setup Conditions

Sr. No.	Parameters	Conditions
1	Mach number	2.2
2	Pressure	39408.65 Pa
3	Temperature	161.65 K
4	Turbulence Model	Standard k-ω (2-equation)
5	Energy Equation	On
6	Specific Dissipation Rate	Second-order Upwind
7	Spatial Derivatives in Governing Equations	Second-order Upwind
8	Turbulent Kinetic Energy	Second-order Upwind

Additionally, a freestream Reynolds number of 2.66×10^7 is specified at the pressure far-field at the inlet boundary.

4. Results and Discussion

4.1 Comparative Performance Analysis of the Air-intakes

The better working air-breathing engine requires an efficient air-intake. The quantity and quality of air-flow supplied through the air-intake consequently affect the combustion characteristics, engine thrust, fuel consumption and overall performance of the engine. The total pressure recovery is one of the parameters by which the engine efficiency can be determined. Total pressure recovery is the ratio of the total pressure of air-flow at the engine face to that of the freestream. Higher total pressure recovery in turn provides better engine efficiency. So, the main aim is to improve total pressure recovery.

In this work, results pertaining to four cases – intake without a bump, intake with a single bump and intakes with two different double-bump locations are studied. The Mach contours for all four cases are as shown in the figures below. Figure 7 represents an intake with no bumps. Here, oblique shock waves are generated at the turn in the ramp surface, due to higher wedge angle. These shock waves subsequently get reflected by the cowling surface introducing an oblique shock at the throat section. Due to this shock, the Mach number of air-stream reduces. Figure 8 shows the Mach contours in an intake with a single bump. The oblique shock at the bump is much stronger than in Figure 7, as is evident from the lower Mach number downstream of the shock. The effect of this stronger shock is carried forward by the stronger reflected shock at the cowling surface. The single bump in Figure 8 therefore gives better compression than intake without the bump in Figure 7.

Dhanlobhe *et.al.*,[13] explored the possibility of further improving the air-intake by introducing two bumps on the ramp surface – one upstream of the turn in the surface and the other bump downstream of the turn. This resulted in three oblique shocks (one at the turn and one each at the bumps). This set of three shocks does not give a strong reflected shock at the cowling. As a result, the performance of this double-bump intake is similar to the single-bump case.

In this work, we carefully investigated the above work by Dhanlobhe *et.al.*,[13]. It is observed that the oblique shock generated at the bump upstream of the turn does not get reflected off the cowling surface as can be seen from the Mach contours in Figure 9 and pressure contours in Figure 13. We therefore engineer both the bumps downstream of the turn expecting the oblique shocks from both the bumps to get bounced off the cowling surface as in Figures 10 and 14. Results from pressure contours clearly show a larger static pressure at the exit of the intake (which in turn is the inlet to the combustion chamber). A comparison of Figure 9 with 10, and Figure 13 with 14, shows that the new double-bump location results in a lower Mach number and greater static pressure at the exit of the intake. Both these conditions are favourable for better combustion.

4.2 Mach Contours

The Mach contours obtained from the computational simulation for the four intake configurations are shown in Figures 7-10.

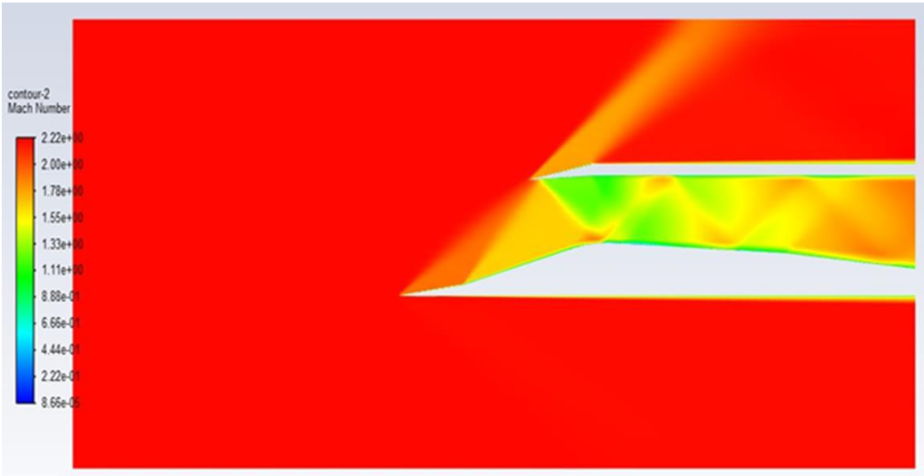

Fig. 7. Intake without bump

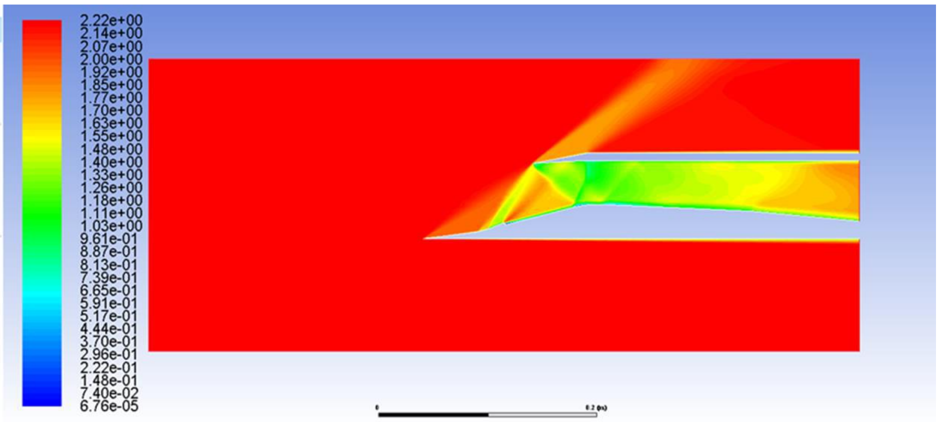

Fig. 8. Intake with single bump

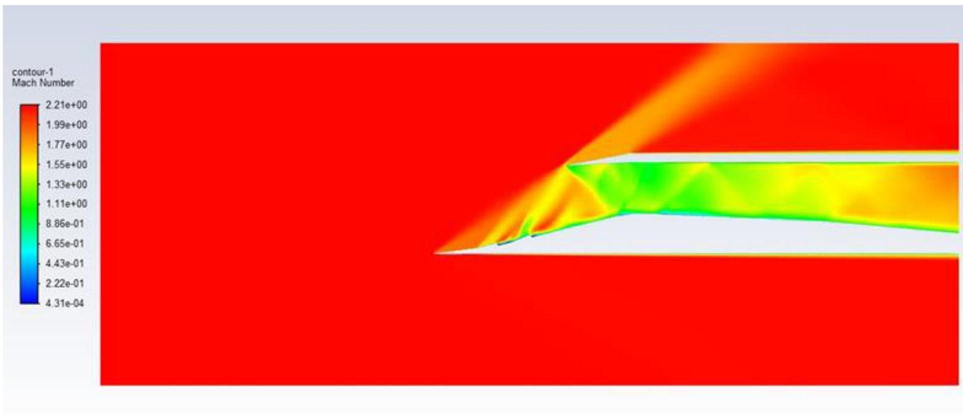

Fig. 9. Intake with double-bump studied by Dhanlobhe *et.al.*,[13]

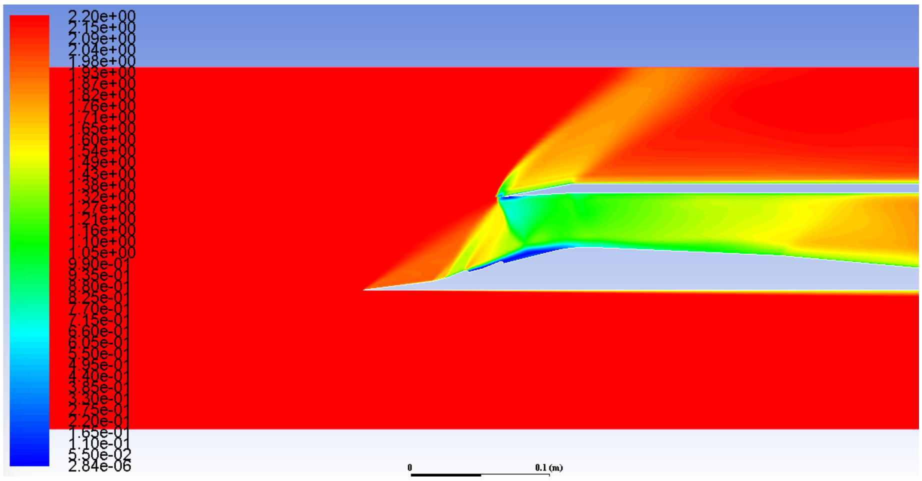

Fig. 10. Intake with double-bump proposed in the present work

4.3 Static Pressure Contours

The static pressure contours obtained from the computational simulations for the four intake configurations are shown in Figures 11-14.

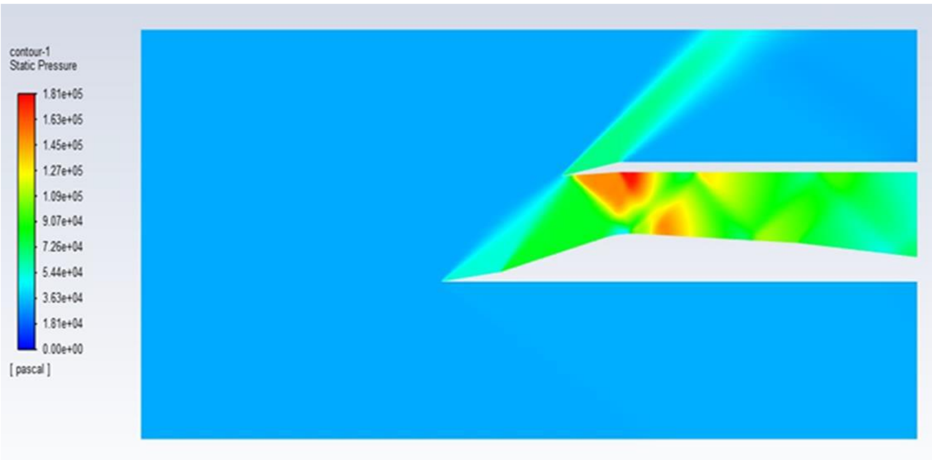

Fig. 11. Intake without bump

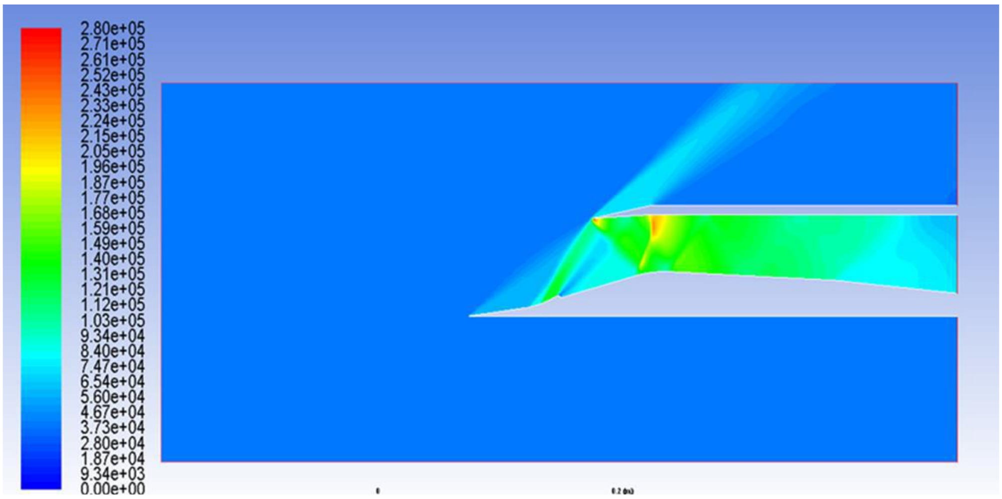

Fig. 12. Intake with single bump

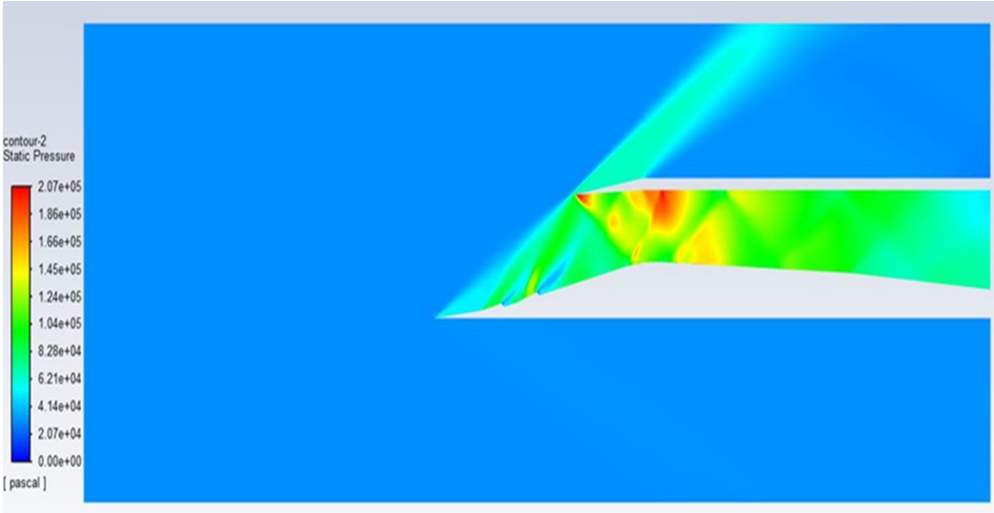

Fig. 13. Intake with double-bump studied by Dhanlobhe *et.al.*,[13]

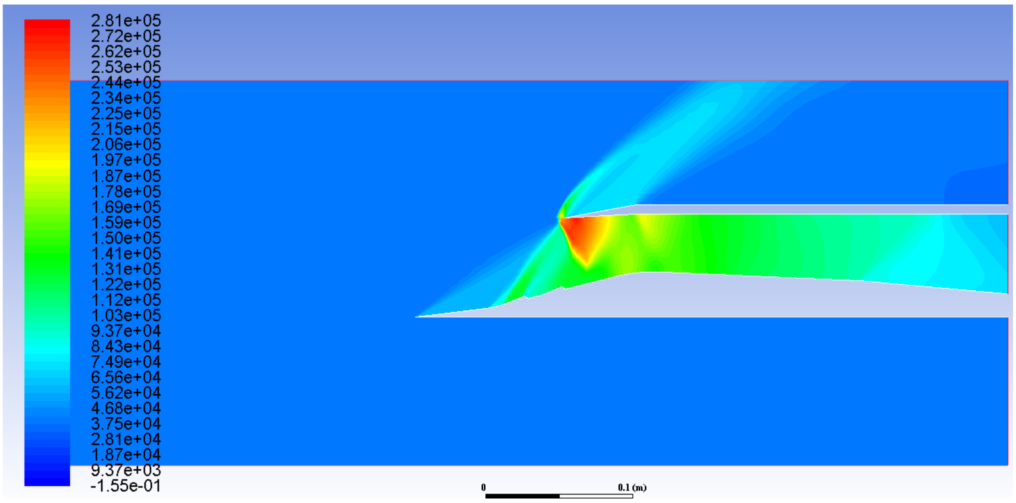

Fig. 14. Intake with double-bump proposed in the present work

The values of the Mach number and pressure recovery at the exit of the four supersonic air-intake configurations are listed in Tables 2 and 3 respectively. Clearly, the air-intake having the double-bump located as proposed in the present study has the lowest Mach number and highest pressure recovery at the exit. These are the desired objectives for more efficient combustion downstream. Hence, the double-bump located based on the principles of high-speed aerodynamics is demonstrated to be the superior design.

Table 2
Mach number at outlet of the air-intake

Intake Configuration	Mach Number at Outlet
a. Intake without bump	1.002
b. Intake with single bump	0.98
c. Intake with double-bump studied by Dhanlobhe *et.al.*,[13]	0.98
d. Intake with double-bump proposed in the present work	0.98

Table 3
Total pressure recovery at outlet of the air-intake

Intake Configuration	Total pressure recovery
a. Intake without bump	0.8642
b. Intake with single bump	0.9424
c. Intake with double-bump studied by Dhanlobhe *et.al.*,[13]	0.9236
d. Intake with double-bump proposed in the present work	0.9775

5. Conclusions

While there was a degradation in performance of the supersonic air-intake when Dhanlobhe *et al.,* [13] introduced a double bump on the inlet ramp surface, this work analyzed the problem and identified that the location of the double-bump has an effect on the performance of the air-intake, due to the resulting location of the shocks.

Shifting both the bumps downstream of the turn in the ramp surface, led to oblique shocks being confined to the interior of the cowling, thereby producing stronger reflected shocks inside the air-intake. This finally resulted in higher pressure recovery and lower Mach number at the exit of the intake. Future studies can further investigate this to arrive at an optimal location and geometry of the double-bump.

References

[1] Sepahi-Younsi, Javad, Behzad Forouzi Feshalami, Seyed Reza Maadi, and Mohammad Reza Soltani. "Boundary layer suction for high-speed air intakes: A review." *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 233, no. 9 (2019): 3459-3481. https://doi.org/10.1177/0954410018793262

[2] Kurth, Guido, and Christoph Bauer. "Air intake development for supersonic missiles." In *44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, p. 5263. 2008. https://doi.org/10.2514/6.2008-5263

[3] Saunders, J., and T. KEITH, JR. "Results from computational analysis of a mixed compression supersonic inlet." In *27th Joint Propulsion Conference*, p. 2581. 1991. https://doi.org/10.2514/6.1991-2581

[4] Slater, John. "Design and analysis tool for external-compression supersonic inlets." In *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, p. 16. 2012. https://doi.org/10.2514/6.2012-16

[5] B Saheby, Eiman, Xing Shen, and Anthony P. Hays. "Design and performance study of a parametric diverterless supersonic inlet." *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 234, no. 2 (2020): 470-489. https://doi.org/10.1177/0954410019875384

[6] Wong, Wai Sam, Ning Qin, and Nick Sellars. "A numerical study of transonic flow in a wind tunnel over 3D bumps." In *43rd AIAA Aerospace Sciences Meeting and Exhibit*, p. 1057. 2005. https://doi.org/10.2514/6.2005-1057

[7] Soltani, M. R., and R. Askari. "On the performance of a body integrated diverterless supersonic inlet." *Aerospace Science and Technology* 91 (2019): 525-538. https://doi.org/10.1016/j.ast.2019.05.045

[8] Khan, Ambareen, Nurul Musfirah Mazlan, and Mohd Azmi Ismail. "Velocity Distribution and Base Pressure Analysis of Under Expanded Nozzle Flow at Mach 1.0." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 92, no. 1 (2022): 177-189. https://doi.org/10.37934/arfmts.92.1.177189

[9] Kim, Sang Dug. "Aerodynamic design of a supersonic inlet with a parametric bump." *Journal of Aircraft* 46, no. 1 (2009): 198-202. https://doi.org/10.2514/1.37416

[10] Kim, Sang Dug, and Dong Joo Song. "Numerical study on performance of supersonic inlets with various three-dimensional bumps." *Journal of mechanical science and technology* 22 (2008): 1640-1647. https://doi.org/10.1007/s12206-008-0503-9

[11] Askari, R., M. R. Soltani, K. Mostoufi, A. Khajeh Fard, and M. Abedi. "Angle of attack investigations on the performance of a diverterless supersonic inlet." *Journal of Applied Fluid Mechanics* 12, no. 6 (2019): 2017-2030. https://doi.org/10.29252/jafm.12.06.29880

[12] Chandler, Frank O., and Ricardo Montes. "A CFD investigation of a diverterless supersonic inlet of ellipsoidal entrance shape." In *AIAA Propulsion and Energy 2019 Forum*, p. 4274. 2019. https://doi.org/10.2514/6.2019-4274

[13] Dhanlobhe, Mayuri M., Pritee D. Nale, Vishal S. Shejwal, Pratik A. Suryawanshi, and Devabrata Sahoo. "Performance Study of Supersonic Air-intake Adopting Double Bump." In *2021 IEEE Pune Section International Conference (PuneCon)*, pp. 1-4. IEEE, 2021. https://doi.org/10.1109/PuneCon52575.2021.9686525

[14] Das, Sudip, and Jai Kumar Prasad. "Cowl Deflection Angle in a Supersonic Air Intake." *Defence Science Journal* 59, no. 2 (2009). https://doi.org/10.14429/dsj.59.1496

[15] Hakim, Kbab, Hamitouche Toufik, and Y. Mouloudj. "Study and simulation of the thrust vectoring in supersonic nozzles." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 93, no. 1 (2022): 13-24. https://doi.org/10.37934/arfmts.93.1.1324