Physics of Fluids

Response to "Comment on 'A new approach for the design of hypersonic scramjet inlets'" [Phys. Fluids 32, 079101 (2020)]

Cite as: Phys. Fluids **32**, 079102 (2020); https://doi.org/10.1063/5.0012513
Submitted: 07 May 2020 • Accepted: 22 June 2020 • Published Online: 15 July 2020

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https://doi.org/10.1063/5.0012513

In our previous article (henceforth referred to as R & V[1]), we have presented a new approach for the design of hypersonic scramjet inlet. This new approach aims to obtain an optimal inlet geometry that has maximum total pressure recovery at the design criterion of the *shock-on-lip* condition for a given design Mach number. The performance of scramjet inlet geometries generated using this approach has been reported for 1D, 2D inviscid, and 2D viscous effects. It has been observed that even though the *shock-on-lip* condition has been imposed during the inlet design phase, it was not satisfied in our computational fluid dynamics (CFD) simulations for the intended design Mach number. Hence, simulations were performed for various off-design Mach numbers to find the actual Mach number at which the *shock-on-lip* condition was satisfied. Based on simulations, a correlation equation has been reported, which finds the actual Mach number that satisfies the *shock-on-lip* condition for a given design Mach number.

In the comment on our publication (R & V[1]) by Brahmachary *et al.*,[2] it has been reported that the nomenclature for n, i.e., the number of external shocks, has been misinterpreted as the total number of shocks in Fig. 3 of our work[1] during a comparison with an earlier work of Smart.[3] We agree with this comment; however, this finding does not change our previous results[1] but only requires a change in comparison of results by Smart.[3] Hence, a corrected comparison of our results with that by Smart[3] is presented in Fig. 1 with the same design methodology reported in our work.[1] Additionally, in Sec. II A of our work,[1] SPR = 0.01 needs to be read as SPR = 1, and the denominator in Eq. (2) needs to be read as $M_1^2(\gamma + \cos 2\beta) + 2$ instead of $M_1^2(\gamma + \cos 2\beta + 2)$. The following observations can be made from Fig. 1:

1. It can be noted that the total pressure recovery obtained by our design procedure shows an improvement over the earlier work by Smart,[3] especially in the hypersonic speed regimes above Mach numbers greater than 6–6.5.
2. When m, i.e., the number of internal shocks, is increased, the corresponding difference in total pressure recovery between our work[1] and the work of Smart[3] improves drastically.

The above results are still in agreement with the conclusions presented in our work[1] but are in contrast with the comments made by Brahmachary *et al.*[2] to our article. To understand this disparity, we compare our results with Brahmachary *et al.*[2] in Fig. 2 where the differences between total pressure recovery predicted using our approach[1] and the approach used by the Brahmachary *et al.* (see Fig. 1 of the comment article[2]) for the $n = 2$, $m = 2$ case are shown. From Fig. 2, it is observed that Brahmachary *et al.*[2] predicted the total pressure recovery to be much lower than that of our approach.[1] This indicates that Brahmachary *et al.*[2] have not been successful in reproducing our approach.[1]

Our design is an iterative approach and obtains a set of optimal turning angles and dimensions of the scramjet inlet to improve the overall total pressure recovery for a given design Mach number. As an example, for a design Mach number of $M = 10$ and $n = 2$, $m = 2$ case, the corresponding optimal turning angles are found to be 3.841°, 4.424°, 5.106°, and 5.912°. Misinterpretation of our approach by Brahmachary *et al.*[2] leads to a design of non-optimal geometry, resulting in a low total pressure recovery when compared to our approach.[1] In addition to that, they might have not implemented the correct Eq. (2) to obtain turning angles because of a typographical mistake in Eq. (2) of our previous work.[1]

In our work,[1] we have reported that when 2D inviscid and viscous CFD simulations were performed on the designed intake, the *shock-on-lip* condition was not satisfied. Brahmachary *et al.*[2] tried

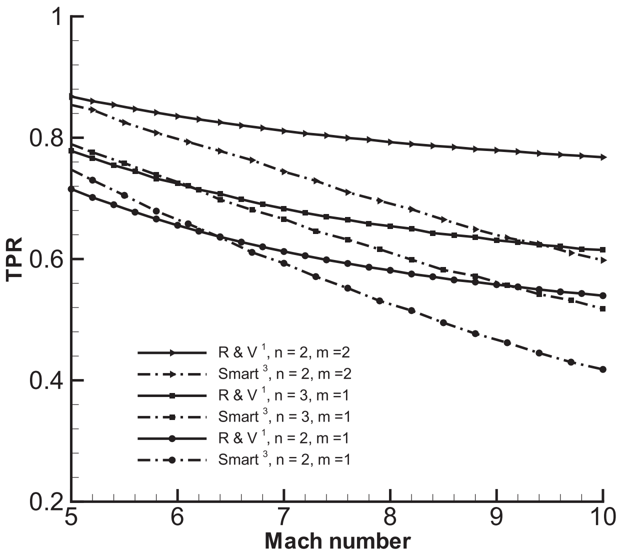

FIG. 1. Variation of total pressure recovery with Mach number.

to reproduce our results for Mach 8 geometry using 2D inviscid simulations and reported that the *shock-on-lip* condition has been satisfied. As mentioned earlier, Brahmachary *et al.*[2] could not reproduce our design procedure. Hence, they have performed simulations on a different geometry compared to ours.[1] This is clear upon close comparison of Mach 8 geometry used by Brahmachary *et al.* (see Fig. 2 of the comment article[2]) and ours[1] (see Fig. 10 of our article[1]), and it can be observed that both the geometries are different. Intake ramp angles of Brahmachary *et al.*[2] appear to be at least 20° higher than our Mach 8 geometry. It can be noted that to achieve the *shock-on-lip* condition, either free-stream Mach number can be increased

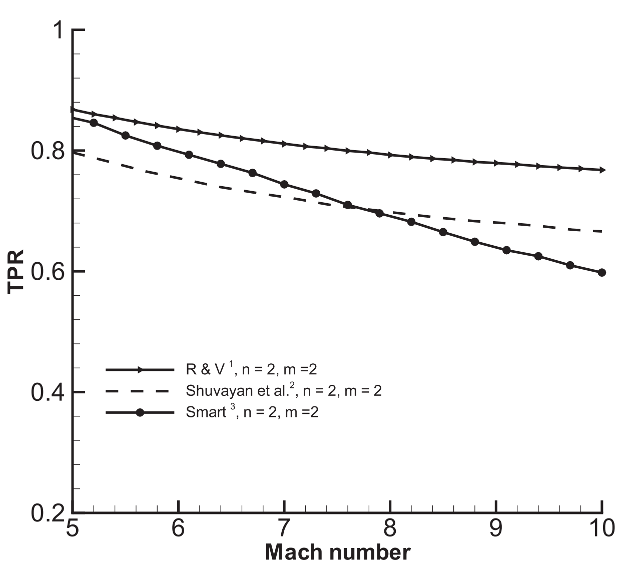

FIG. 2. Variation of total pressure recovery with Mach number.

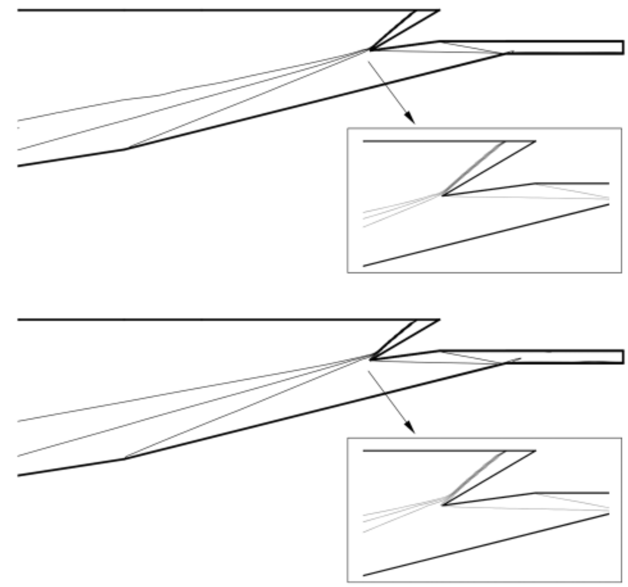

FIG. 3. Mach contours (min: 3.83, Δ: 0.65, and max: 7.08) for M = 8 geometry for constant specific heat (top) and variable specific heat (bottom).

or ramp angles can be adjusted. It appears that the latter is done by Brahmachary *et al.*,[2] and hence, a direct comparison of the results cannot be made.

Brahmachary *et al.*[2] also claimed that the differences between 1D and 2D computations are due to specific heat being constant and variable, respectively, instead of 2D effects. However, in the absence of results by Brahmachary *et al.*[2] to understand the claim, we have performed 2D inviscid simulations on Mach 8 intake geometry for $n = 3$, $m = 2$, and the results are reported in Fig. 3 and Table I for constant specific heat and variable specific heat with temperature. From Fig. 3, one can notice that shock positions remain similar for specific heats being either constant or variable, and also, a constant specific heat assumption did not necessitate a *shock-on-lip* condition. However, we do agree that the magnitude of flow field parameters is a function of specific heat, and the same is reported in Table I. Also, our work[1] considers variable specific heat in all our CFD simulations.

TABLE I. Comparison of results for constant and variable specific heat assumption for Mach 8 geometry for $n = 3$, $m = 2$.

	Present 1D (constant C_p)	Present 2D (constant C_p)	Present 2D (variable C_p)
SPR_{is}	50.05	61.28	66.4
TPR_{is}	0.829	0.663	0.68
M_{is}	4.0	3.756	3.75
$Temperature_{is}$	...	770	873
C_p (J/Kg K)	1006.4	1006.4	1096.55
γ_{is}	1.4	1.4	1.35

Differences between the results of Brahmachary *et al.*[2] (see Table I of the comment article[2]) and ours[1] can be attributed to the fact that intake geometries are different. However, it is observed that total pressure recovery for 2D inviscid simulations reported by Brahmachary *et al.*[2] is higher than 1D results. It is highly unlikely to obtain a higher total pressure recovery in 2D simulations when compared to 1D results as the latter is only a set of gas dynamic relations, which does not consider shock–shock interactions, 2D effects, and numerical dissipation effects, which would reduce the total pressure recovery. The solver used in the present study by Brahmachary *et al.*[2] as reported in their earlier work[4] was only tested for the simplified single ramp scramjet intake geometry, whereas the current problem involves multi-shock scramjet intake, which requires modeling of complex flow fields. In addition to that, they have not validated their solver with experimental results including viscous effects.

Our investigations show that unsuccessful interpretation of our intake design methodology led to inaccurate conclusions by Brahmachary *et al.*,[2] which have been addressed in this article. Figure 1 reconfirms our earlier conclusions that the current intake design methodology is better than earlier work of Smart[3] in the hypersonic operational regime of scramjet. It is also indicated that conclusions on operability and performance of a scramjet inlet based on 2D inviscid simulations as done by Brahmachary *et al.*[2] would not be realistic, and hence, viscous simulations as reported in our earlier work[1] are needed. Also, the linear relation presented in our work applies only for correcting for viscous results and is not valid for current 2D invisicd simulations. By using this correction, the *shock-on-lip* condition will be ensured in the viscous flow regime, as demonstrated in our earlier work.[1]

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