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High-Fidelity Numerical Analysis of Supersonic Shock Boundary Layer Interaction in Propulsion

Kaleeswaran P[1], *, S. Yuvaraj[2]
[1]Associate Professor, Annasaheb Dange College of Engineering and Technology, Maharashtra, India
[2]Professor, Annasaheb Dange College of Engineering and Technology, Maharashtra, India
Email: pk_aero@adcet.in

Abstract-The separation bubbles in the shock-wave and boundary-layer interaction (SBLI) region have adverse effects on inlet pressure recovery, bring about unsteady loading, and are a threat to the operability of supersonic propulsion systems. The focus of this survey is on recent numerical studies of separation-bubble prediction, shock-train coupling, sidewall confinement, transition and control in propulsion-related geometries. Although the literature is not presented chronologically by date, it is sorted sequentially by fidelity level, geometry, unsteadiness mechanism, validation path and control-technology approach. The review demonstrates that Reynolds-averaged Navier–Stokes (RANS) is still very useful for preliminary design, that hybrid RANS–large-eddy simulation (LES) is currently the most suitable tool available for unsteady engineering applications and that direct numerical simulation (DNS)/LES is still primarily a physics database. The primary difference lies in a field-stable separation-bubble closure that is numerically robust and will readily adjust across Mach number, Reynolds number, wall temperature, or inlet geometry.

key words: Boundary-layer interaction; separation bubble; supersonic inlet; scramjet isolator; RANS; LES; DNS; propulsion systems.

1. Introduction

Supersonic propagation systems work by compressing the air that enters them before it is burned. This is often accomplished with ramps, cowl shocks, curved walls, isolators and diffusers. When the shock wave interacts with the boundary layer that develops along the wall, the flow near the wall may not have sufficient momentum to withstand the sudden increase in pressure. This separation, in turn, creates a recirculating separation bubble. The effects of the bubble include a shock foot, thickening of the boundary layer, loss of total-pressure recovery, and the creation of broadband wall-pressure fluctuations. This is not a minor, localized distortion in a ramjet or scramjet inlet. It can alter the effective throat, the shock train position, the flow distortion at the engine face and the margin to inlet unstart [1]–[3]. This is a timely subject, as current trends in the design of propulsion systems are towards higher Mach numbers, inlets with small size, reusable high-speed vehicles, and design cycles utilizing digital design.

These systems have a short compression length, coupled with a high pressure rise. Thus, separation bubble phenomena are forced to be strongly associated with the 3-D sidewall effects, transition, heating, shock-train movements and active or passive control devices. Previous work performed in canonical studies formulated the fundamental physics, though intake behaviour found in recent studies is not just a two-dimensional compression ramp problem. Sidewalls, confinement, cowl-shock impingement and ramp-isolator junction details may dominate the low-frequency dynamics and the mean separation footprint [3]–[7].

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Corresponding author. E-mail address: pk_aero@adcet.in
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Numerical simulation is desirable because it allows the entire flow field to be displayed, whereas experiments generally sample it only through limited wall pressures, schlieren photography, particle image velocimetry (PIV), or pressure-sensitive paint (PSP). However, the outcome is strongly controlled by the numerical choice. When flow transition and separation are of interest or when the flow is curved or confined in three dimensions, steady RANS can provide a low-cost prediction of the gross pressure rise but can also give an inaccurate prediction of the separation point and the extent of separation. If the physics and boundary conditions modeled are conducive to a low-frequency motion, then unsteady Reynolds-averaged Navier–Stokes (URANS) may be able to capture it. Hybrid RANS/LES and detached-eddy simulation (DES) are more credible engineering approaches for unsteady separated flows but are sensitive to the grid and the inflow turbulence. Although wall-resolved LES and DNS can be invaluable for the discovery of mechanisms, the stability analysis and the creation of databases, their cost for full propulsion geometries at high Reynolds numbers is still relatively high [8]–[11].

The existing reviews pertain to SBLI physics and control in general, including external and internal flows [2], [12]. A recent review also gives a description of the diversity of three-dimensional interactions [12]. Although the contributions are valuable, they are not solely based on the narrow objective of numerical characterization of separation bubbles for propulsion performance. The missing synthesis is thus not a description of SBLI per se but a more design-oriented map that indicates what can be realistically used for propulsion-system decisions, what remains in the realm of simulation demonstrations, and what evidence is needed to elevate from the canonical studies to those that can support propulsion-system decisions. The scope of this survey is to focus on supersonic and low-hypersonic Mach-number flow around inlet, isolator, ramp, cowl, duct and related canonical configurations where shock-induced separation impacts propulsion performance [13].

Studies conducted primarily since 2015 will be included in the review, as this is the time in which high-fidelity simulation, sidewall-confined configurations, shock-train dynamics, adaptive control, and separation-length scaling have seen the highest levels of development. It does not include purely transonic aircraft-wing buffet, detonation-only studies, or combustor chemistry, except when directly related to altering SBLI separation or shock-train behavior. Four questions pertaining to the review approach were used. First: Are separation length, reattachment, pressure plateau, heat flux, shock motion, distortion, or control benefits to be predicted? Second: Numerical fidelity: RANS, URANS, LES, DNS, DES, stability analysis, modal analysis, reduced order modelling? Third, is there any validation evidence (pressure distribution, PIV, PSP, schlieren, or companion experiment)? Fourth, is it strictly a high-cost physics investigation or can it be applied in design? These questions result in the taxonomy presented in Figure 1 and in the following comparative tables.

This manuscript contributes to the problem of separation-bubble prediction in propulsion-relevant SBLI in particular. The taxonomy categorises the literature according to the numerical route and how beneficial it is for design; the critical analysis highlights the realistic and simulation-only methods; and the future directions outline a new challenge: design of a field-stable separation-bubble closure that is accurate across Mach-number variation, Reynolds-number variation, wall-temperature variation, sidewall confinement and shock-train motion due to back-pressure.

2. Review Scope and Search Methodology

The selected emerging subfield is the characterization of the separation bubble in quantitative terms, in propulsion-relevant SBLI. It is therefore positioned between basic high-

speed-flow physics and the design of the engine inlet. This field is active as new work continues to examine the use of high-fidelity simulations, sidewall-resolved computations, shock-train/isolator studies, and flow-control concepts including notches, backward-facing steps, micro-vortex generators, transverse jets, plasma jets and secondary recirculation jets [11], [14]–[19]. This survey is novel in its boundary, which is implementation-oriented. It does not discuss each SBLI paper, but rather asks how a numerical method enables a designer to estimate the size of separation, the unsteady pressure loading and the inlet performance.

This is of critical importance because a correct graphical shock pattern cannot suffice. It is also essential that a propulsion model be capable of predicting pressure recovery, distortion, heat flux, shock-train position and control penalty under off-design operation. The literature was split into seven categories: canonical numerical physics, sidewall & confinement, transition and inlet turbulence sensitivity, shock-train & back-pressure coupling, flow-control technologies, high-fidelity solver frameworks, and scaling/closure models. Table 1 summarizes the taxonomy. Table 2 presents the reporting framework used for propulsion SBLI evaluation. Major numerical routes are compared in terms of the maturity of their implementation in Table 3.

3. Classification of Numerical Approaches

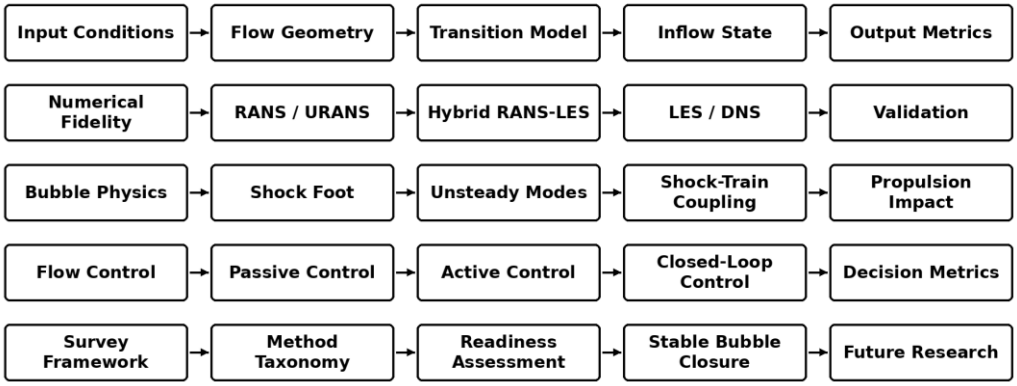


Figure 1: Architecture diagram for SBLI separation bubbles

Table 1 Studies on separation-bubble prediction and control in propulsion-relevant SBLI.

Taxonomy class	Typical configuration	Main output	Representative references
Canonical ramp/impinging-shock simulations	2-D/3-D ramp, flat plate, oblique shock	Separation and reattachment length; shock-foot motion	[4], [8], [20], [21]
Sidewall and confinement effects	Rectangular channel, intake sidewall, confined ramp	Spanwise motion; corner separation; confinement-induced unsteadiness	[3], [5]–[7], [22]
Transition-sensitive SBLI	Laminar/transitional boundary layer; forced transition	Onset of separation; bubble intermittency; transition location	[20], [23], [24]
Shock-train/isolator coupling	Scramjet isolator, curved duct, cavity-isolator	Shock-train length, oscillation, back-pressure response	[11], [15]
Passive and active control	micro-vortex generator (MVG), step, notch, jets, plasma, magnetohydrodynamic (MHD)	Separation suppression; pressure recovery; loss penalty	[14], [16]–[19], [25], [26]
Scaling and closure	Multi-Mach, multi-	Universal scaling and	[21], [27]

models	Reynolds datasets	reduced closure variables	
Solver and database frameworks	OpenSBLI, DNS/LES databases, modal analysis	Reproducible high-fidelity cases; stability modes	[9], [10]

3.1 RANS and URANS Modeling Approaches

Despite the fact that RANS continues to be the most popular initial inlet and isolator screening tool, it still provides a low-cost solution for many geometry iterations. It can be used to predict pressure recovery, approximate separation point, and the impact of simple design modifications. This can be used to determine the thrust for early propulsion design. The weakness is that separation bubbles are not only mean flow objects. Their size is determined by the amplification of turbulence, the movement of shocks, transition state, and three-dimensional separation topology. Such phenomena are frequently embedded in the turbulence-model constants.

A RANS result can thus appear smooth and set, yet produce an incorrect separation length. URANS adds time dependence; however, the physics are not necessarily solved. It is beneficial when the unsteadiness is dominated by one of the large-scale modes, such as a shock-train or inlet mode. It is weak whenever low-frequency forcing requires broadband incoming turbulence, shear layer instability, or three-dimensional motion at the sidewalls. For this reason, either RANS or URANS is a reasonable candidate for screening; however, they must be calibrated to experiments or to high-fidelity data before they can be used for guaranteed performance [1], [2], [27].

3.2 Advanced Turbulence Simulation Techniques

Shock-induced separation is seen most clearly by DNS and wall-resolved LES. They describe the breakdown of shear-layer structures, wall-pressure fluctuations, low-frequency shock motion and the detailed separation-to-reattachment process. Research on transitional interactions, high-Reynolds-number effects and dynamic linear response have helped to elucidate unsteadiness caused by upstream disturbances as well as separated shear layers [8], [9], [20], [23], [28], [29]. The biggest drawback is price. Even a full propulsion inlet at high Reynolds number, imposing real thermal boundary conditions, and a long isolator is too costly for regular wall-resolved LES or DNS. Hybrid RANS-LES and DES are the most practical near-term evolution for unsteady engineering. They are able to capture large separated structures and shock motion without a prohibitive cost near the wall. Their danger lies in the grey-area modelling – if the grid, model switching and inlet turbulence are not treated carefully the result can be a costly URANS calculation. Hybrid methods are best supported by grid refinement, validation with experimental wall-pressure measurements or PSP, and spectral checks [3], [11], [26].

3.3 Sidewall and Confinement Effects

Recent literature clearly indicates that sidewall effects are significant and cannot be treated as minor corrections. Sidewalls in narrow intakes or test sections introduce changes in the main separation bubble, corner separations and spanwise pressure gradients and can trigger low-frequency modes. According to the sidewall-resolved numerical study conducted in 2015 by Wang et al., and subsequent studies concerning sidewall confinement/compression ramps and sidewall-confined interactions, a nominally two-dimensional SBLI can be strongly three-dimensional [4]–[7], [22]. This is important for propulsion because the flow does not enter a two-dimensional combustor. The cross-stream non-uniformity affects the engine-face distortion, shock-train stability, and pressure recovery. A separation-bubble model without sidewall effects may underpredict the distortion as well as underestimate the effectiveness of

control devices. The present fashion is to combine sidewall-resolved simulation and global modes, SPOD/DMD and the measurement of pressure fields to distinguish which structures are design-relevant.

3.4 Shock–Isolator Coupling Analysis

The isolation of the separation bubble located near the ramp or cowl from the downstream isolator is not possible. Upstream pressure rise is modified by the shock train, which is moved by back-pressure. Shock-train/boundary-layer interaction yields moving compression systems, recirculation zones, and coherent pressure waves as shown in the concave isolator channels and cavity-isolator configurations [11], [15]. This is the most important justification for abandoning single-ramp simulations when it comes to propulsion design. Even a method that is able to predict the bubble accurately for a given external shock may be invalid when combustor back-pressure varies. Future simulations should, therefore, be coupled between separation-bubble inlet flow and the respective isolator shock-train behavior and should include shared parameters such as shock-train length, oscillation frequency, pressure recovery or distortion coefficient.

3.5 Flow-Control Technologies

Control methods are divided into passive, active and adaptive. Passive control can use devices such as bumps, backward-facing steps, notches and micro-vortex generators, which are energy-free. Their disadvantage is the off-design penalty: a device that reduces separation at one Mach number may result in increased loss or heat load at another Mach number [14], [16], [26]. Active technologies such as jets, plasma jets, MHD forcing, and secondary recirculation jets must be adapted to changing circumstances; however, they require power, sensors and actuators and reliable control laws [17]–[19], [25]. This is not the best path forward just because it is the greatest suppression of separation. In reality, the design goal is one of net propulsion benefit, that is, less distortion and more pressure recovery without a lot of mass, power, thermal, or maintenance penalties. Hence it is recommended that both the flow-field improvements and the system cost be reported in a numerical study.

3.6 Method-Wise Technical Analysis

The reference cases for model development are still the canonical compression-ramp and impinging-shock cases. They are also helpful for measurement and simulation with known boundary conditions for the shock generator, incoming boundary layer, and separated shear layer. Their downfalls are also obvious – a cowl lip, isolator back pressure, corner separation, or combustor feedback are not in a canonical ramp. Thus, the implications of canonical cases should be regarded as calibration cases of mechanisms, not as propulsion-prediction cases [4], [8], [20]. SBLI is a distinct category as the separation bubble can vary in size and intermittency when the separation is preceded by a laminar boundary layer and followed by a turbulent boundary layer. Results from forced-transition experiments and transitional calculations confirm that a slight change upstream can lead to a change in reattachment and hence a change in the shock motion's spectral content [20], [23], [24].

For a real inlet, this translates to the requirement to document the roughness level, the wall temperature and the freestream disturbance level. If no transition assumption is presented, a simulation will be unable to be fully interpreted. The most crucial link between basic SBLI and propulsion hardware is sidewall-resolved studies. In a rectangular intake, the sidewall boundary layers are not neutral. They communicate with the main shock system, develop corner vortices and introduce spanwise pressure gradients. Recent 2-D experimental studies of unsteadiness in confinement as well as experimental pressure-field measurements with sidewalls demonstrate potentially strong three-dimensionality of the unsteadiness at low

frequencies [5]–[7], [22]. For this reason, a two-dimensional design margin for engine-face distortion can be misleading.

Shock-train simulations show the downstream portion of the same problem. While the isolator contains the pressure fluctuations between the inlet and the combustor, it also produces a long string of shocks, separated areas, and pressure waves. The shock train can interact with cavities or curved walls [11], [15] when there are changes in back-pressure. Hence, a model of the inlet separation bubble should not end at the occurrence of the first interaction. Testing should be carried out using back-pressure sweeps, and should indicate the relationship between upstream separation and downstream shock-train movement. There are two types of flow-control studies, one related to geometry and one related to energy input. Notches, backward-facing steps, bumps, bleed, and micro-vortex generators are examples of geometry control. These can be more readily formulated and tested, and an optimum operating point may be quite limited.

Energy-input control encompasses transverse jets, secondary recirculation jets, plasma jets, and magnetic-field-based control. These approaches are potentially adaptive, but power consumption, cooling, durability and sensor reliability [16]–[19], [25] are critical to their propulsion value. In addition, post-processing is emerging as being as relevant as simulation, as revealed by the literature. When compared to the mean contour alone, modal decomposition, shock-foot tracking, pressure spectra and separation-foot probability maps provide more useful information. An experimental test section must be equipped with the capacity to determine whether a bubble will be steady, breathing, sweeping spanwise, or interacting with a shock train. Very different unsteady loads and distortion risks, may be encountered with the same mean separation length. Finally, a detailed scaling study [21], [27], [30] of the complex separated flow is useful because it attempts to break down the flow into scalable length-scale relations and is the most recent study. But scaling by itself cannot be equated to simulation.

Table 2 Propulsion SBLI Reporting Framework

Protocol item	Minimum report	Why it matters	Common weakness
Inflow state	Mach, Reynolds number (Re), boundary-layer thickness, turbulence/transition model	Controls separation onset	Often underreported
Thermal condition	Adiabatic/isothermal/cooling wall temperature ratio	Changes density and separation response	Usually simplified
Domain and sidewalls	Width, sidewall boundary layer, symmetry assumptions	Controls 3-D separation and distortion	2-D assumptions overused
Numerical fidelity	RANS/URANS/DES/LES/DNS with grid and y+ data	Determines credible unsteady content	Grid evidence often insufficient
Bubble metrics	x_s, x_r, L_sep, intermittency, spectra	Connects flow physics to design	Mean contours overused
Propulsion metrics	Pressure recovery, distortion, shock-train length, heat load	Shows system benefit	Flow improvement not linked to engine outcome
Validation	Wall pressure, PIV, PSP, schlieren, or benchmark database	Builds trust in prediction	Many studies are simulation-only
Control cost	Drag/loss, mass, power, cooling, complexity	Determines implementability	Actuator penalty omitted

The scaling is most effective when employed as a check on the predictions provided by the CFD models or as an initial model in uncertainty quantification. It is least effective when used outside the geometry and thermal environment of its origin. A complete evidence chain should therefore include solver and turbulence model, grid resolution, treatment of inflow turbulence/transition, imposed wall temperature condition, domain width, side-wall treatment,

back-pressure imposed, separation metrics reported, the great bulk spectral reported, and at least one validation signal in a good future numerical paper. If this chain is missing, then a result could be scientifically interesting but not that useful to incorporate into propulsion design.

3.7 Evaluation Protocol

3.8 Evidence Levels for Propulsion Analysis

The reviewed studies can be broken into four levels of evidence. Level 1 is a demonstration that is purely numerical and not externally validated. It is good for brainstorming ideas and not so good for design. Level 2 is a wall-pressure/schlieren match to reference data. This is acceptable for a preliminary design. At Level 3, unsteady spectra, separation length, and three-dimensional pressure fields are validated. It is suitable for detailed engineering studies. At Level 4, a prediction is made using SBLI and is related to propulsion parameters such as pressure recovery, distortion, operability margin, and control cost. There are very few Level 4 studies. This evidence-ranking helps to determine why some high-fidelity simulations are not as useful as some lower fidelity studies. While a narrow canonical case can yield great insight into mechanisms, it may give little direct evidence of the system. Even if there are modelling approximations, a carefully validated hybrid simulation of an intake could be more useful for design if it can predict the variables that affect the operation of the engine.

The ultimate research program has both high-fidelity canonical cases for closure development and valid propulsion-scale simulations for implementation. Characterization of separation-bubble phenomena under propulsion conditions should take precedence and the interest of the particular project theme should be on this topic, which is indicated by the title, and not on detailed shock visualization. The numerical study should provide a reproducible plot or map of bubble length, bubble motion, shock-train response, pressure recovery, and distortion, under varying Mach numbers and back-pressures. A map like this would directly aid the process of inlet design and control.

4. Numerical Parameters for Bubble Characterization

A useful numerical study should report more than Mach contours. The minimum bubble metrics are separation point, reattachment point, separation length, shock-foot motion, wall-pressure plateau, heat-flux amplification, and downstream distortion. These quantities connect the computational fluid dynamics (CFD) result to propulsion performance. In a wall-aligned coordinate s, a simple skin-friction definition is

$$x_s = \min \{s : C_f(s) < 0\} \tag{1}$$

$$x_r = \min \{s > x_s : C_f(s) > 0\} \tag{2}$$

$$L_{sep} = x_r - x_s \tag{3}$$

$$\bar{L}_{sep} = (1/T) \int_0^T L_{sep}(t)\, dt \tag{4}$$

$$D_p = [p_{t,max} - p_{t,min}] / \bar{p}_t \tag{5}$$

$$\eta_p = \bar{p}_{t,out} / \bar{p}_{t,in} \tag{6}$$

$$J = w_1(1 - \eta_p) + w_2 D_p + w_3(\bar{L}_{sep} / L_{ref}) + w_4(\dot{Q}_{ctrl} / \dot{Q}_{ref}) \tag{7}$$

Thus, x_s and x_r are the separation and reattachment locations, C_f is the skin-friction coefficient, Lsep is the instantaneous separation length, $\bar{L}_{sep}$ is the time-averaged separation length, D_p is a simple total-pressure distortion measure, and J is a weighted design objective for controlled

SBLI. The equations are kept as simple as possible because the survey is looking for generic instead of solver-specific equations. A good paper will specify where these will come from. For instance, a skin friction time-averaged separation length can also vary from an intermittency-based separation length as measured from the snapshots. The standard deviation and the spectrum of $L_{sep(t)}$ do not only play a role in highly unsteady shock-train cases, but they are as essential as the mean value of $\bar{L}$sep. Here, s denotes the wall-aligned coordinate; T is the averaging interval; $p_{t,max}$, $p_{t,min}$, and $\bar{p}$t denote the maximum, minimum, and mean total pressures; $\bar{p}_{t,out}$ and $\bar{p}_{t,in}$ denote the mean outlet and inlet total pressures; w_1–w_4 are weighting coefficients; L_{ref} is the reference separation length; and $\dot{Q}_{ctrl}$ and $\dot{Q}_{ref}$ are the control and reference rate terms, respectively.

5. Critical Analysis

First, for preliminary implementation issues, calibrated RANS/URANS can be used; second, for final unsteady assessment, hybrid RANS-LES can be used. Although low-cost, high strength, and convenience make RANS an attractive separation-bubble length estimation tool across a wide range of inlet shapes, it should not be relied upon for separation-bubble length estimation under strong sidewall or shock-train coupling or strong transition. URANS can be used for large coherent oscillations, but may lead to model-induced periodicity. The benchmark engineering choice for the present is hybrid RANS-LES since it targets the resolution of the separated shear layer and shock motion without the price of wall-resolved LES. Its drawbacks are grid sensitivity and the need for careful treatment of turbulence phase-in. DNS and wall-resolved LES are largely simulation-based for full propulsion systems; however, mechanisms and closures can be revealed and validated, and they are scientifically the strongest. Even with the use of jets, plasma or MHD, flow-control simulations are promising, but many of these simulations are only partially implementable due to an imperfect modeling of actuator power, thermal durability and the sensor feedback. Passive notching, backward-facing steps, bleed and micro-vortex generators have less authorship, and are easier to manufacture and test, and are more readily implementation-ready although the off-design penalty must be determined.

Table 3 Comparison Based on Implementation Maturity

Method	Strength	Main limitation	Implementation status	Best use
RANS	Fast design sweeps	Weak unsteady separation physics	Ready, but calibration needed	Concept screening
URANS	Captures large coherent modes	Model-driven oscillations possible	Ready for selected cases	Shock-train trend studies
Hybrid RANS-LES/DES	Resolves main separated structures	Grid and inflow sensitive	Most realistic near-term	Final unsteady CFD
Wall-resolved LES/DNS	Best physics detail	Too costly for full inlet	Mostly simulation database	Closure development
Passive control CFD	Simple devices and testing route	Off-design losses	High readiness	Notch, bump, MVG design
Active/adaptive control CFD	Condition-dependent response	Power, sensors, thermal durability	Medium to low readiness	Future smart inlet control

6. Comparative Synthesis of Recent Literature

Table 4 summarizes the propulsion-relevant comparative evidence. The most robust evidence concerns the fundamental relationship among adverse pressure gradient, separation,

shock-foot motion and low-frequency unsteadiness. This is corroborated by DNS/LES, experiments and modal analyses. The transferability is the weakest link. A method optimized for a canonical ramp is not necessarily valid for a curved isolator or cowl-shock interaction or sidewall-confined intake. The most beneficial recent effort has been the transition from a single separation length to a series of coupled design metrics. Whether $\bar{L}_{sep}$ is shorter is not the question for propulsion. The interesting point is whether there is an improvement in pressure recovery, reduction of distortion, reduction of the harmfulness of shock-train motion, and acceptable thermal loads in the practical case.

Table 4 propulsion-relevant decision making.

Focus area	Common evidence	What is mature	What remains weak	Key studies
Separation length scaling	Mean wall pressure, skin friction, x_s/x_r	Useful correlations now emerging	Transfer to full inlet is limited	[21], [27]
Low-frequency dynamics	Pressure spectra, DMD/SPOD, shock tracking	Mechanisms known for canonical ramps	Full-system feedback not closed	[6], [8], [9], [23]
Sidewall effects	3-D separation maps, PSP, confined CFD	Clear evidence of spanwise effects	General closure missing	[4], [5], [7], [22]
Shock train and isolator	Wall pressure, back-pressure sweep	Important trends captured	Combustor coupling still weak	[11], [15]
Passive control	Pressure recovery, separated area reduction	Notches/steps/MVGs testable	Net loss at off-design unclear	[14], [16], [26]
Active control	Jet/plasma/MHD response, actuator location	Simulation benefit shown	Hardware and power cost not mature	[17]–[19], [25]

7. Innovative Challenge

A new challenge being proposed is a field-stable separation-bubble closure for propulsion-oriented CFD. A closure is field-stable if it is able to forecast the separation footprint and its primary unsteady mode for Mach number, Reynolds number, wall temperature, inlet geometry, sidewall confinement and back-pressure. The common methods have limitations—they are accurate in one class of cases but lose accuracy if the boundary-layer state or the downstream-pressure feedback varies. The closure should not be a single empirical formula. It needs to take into account physical variables present in engineering CFD: incoming momentum thickness, pressure rise rate, shock angle, wall temperature ratio, cross-stream confinement ratio, back-pressure ratio and local turbulence/transition indicators. The training and validation database should be furnished by high-fidelity DNS/LES and the closure should be implemented in the practical inlet-design framework used by RANS models and RANS-LES. A field-stable closure could directly support propulsion design. It would also decrease the uncertainty in inlet operability margins, and direct cost-intensive experiments to the most uncertain system regimes, and determine whether a control device would actually help or hinder the overall system. This challenge is timely as high-fidelity databases of flow, rapid pressure imaging, and graphics processing unit (GPU)-ready solvers are now possible but have not yet been incorporated into common propulsion CFD practices [7], [10], [12], [21].

8. Open Challenges and Future Directions

Five gaps should be covered for future research. First, the separation-bubble datasets must be sufficient to form a synergic matrix of the Mach number, Reynolds number, wall temperature, sidewall spacing and back-pressure. Second, there is a need for better grid and inflow guidelines for the use of hybrid RANS-LES for SBLI so that an engineering user can easily reproduce results. Third, in addition to reduced separation area, active control studies

should report actuator power, the thermal durability of the sensors used, the locations of the sensors and net pressure-recovery benefit. Fourth, coupling of inlet/isolator and combustor back-pressure dynamics should be included to capture unstart-relevant feedback. Finally, uncertainty quantification should be regular practice: separation length, shock-train location and distortion should be reported using confidence intervals. The most promising future step is a digital-twin methodology in which experiments provide pressure and optical data, high-fidelity simulation clarifies the physical mechanisms, and reduced closures are used to close the design models with RANS or hybrid RANS-LES.

9. Design Recommendations

Future numerical investigations must be organized not only according to flow visualization but also according to propulsion decisions. The suggested approach is to determine the inlet/isolator operating envelope, prescreen a large number of cases with low-cost RANS, select a representative subset of the RANS cases to run using hybrid RANS-LES or LES, and validate the selected cases using wall pressure, PSP, PIV, schlieren, or an available and accepted high-fidelity database. All numerical results in the final reporting have to be linked to a design consequence. A shortened bubble is beneficial only if it increases pressure recovery, reduces distortion, reduces unsteady loading, and/or increases the operability margin while not adding excessive loss, power demand, thermal risk or mechanical complexity. This design-related reporting format will benefit the use of SBLI simulation in propulsion-system development tasks.

10. Conclusion

Recent numerical studies of shock-induced separation bubbles in supersonic propulsion-relevant SBLI have been reviewed. Advances have been apparent in the state of the art in high-fidelity simulation, studies with sidewall resolution, shock-train analysis and flow-control concepts. However, when it comes to implementation readiness, there is a wide gap. RANS is practical but closure-limited; hybrid RANS-LES is the most realistic and convenient near-term unsteady design tool; DNS or LES is essential as a physics database for closure development; many active-control concepts remain to be proven in hardware. A valuable and central aspect of this survey is a specific taxonomy and critical discussion that links separation-bubble prediction with propulsion performance. The most promising future path is a field-stable separation-bubble closure that is also tested across various Mach numbers, Reynolds numbers, wall temperature, confinement, and back-pressure conditions.

References

[1] D. V. Gaitonde, “Progress in shock wave/boundary layer interactions,” Progress in Aerospace Sciences, vol. 72, pp. 80–99, 2015, doi: 10.1016/j.paerosci.2014.09.002.

[2] W. Huang, H. Wu, Y.-G. Yang, L. Yan, and S.-B. Li, “Recent advances in the shock wave/boundary layer interaction and its control in internal and external flows,” Acta Astronautica, vol. 174, pp. 103–122, 2020, doi: 10.1016/j.actaastro.2020.05.001.

[3] N. Khobragade, S. Unnikrishnan, and R. Kumar, “Flow instabilities and impact of ramp-isolator junction on shock-boundary-layer interactions in a supersonic intake,” Journal of Fluid Mechanics, vol. 953, Art. no. A30, 2022, doi: 10.1017/jfm.2022.933.

[4] B. Wang, N. D. Sandham, Z. Hu, and W. Liu, “Numerical study of oblique shock-wave/boundary-layer interaction considering sidewall effects,” Journal of Fluid Mechanics, vol. 767, pp. 526–561, 2015, doi: 10.1017/jfm.2015.58.

[5] D. J. Lusher and N. D. Sandham, “The effect of flow confinement on laminar shock-wave/boundary-layer interactions,” Journal of Fluid Mechanics, vol. 897, Art. no. A18, 2020, doi: 10.1017/jfm.2020.380.

[6] A. S. Deshpande and J. Poggie, “Large-scale unsteadiness in a compression ramp flow confined by sidewalls,” Physical Review Fluids, vol. 6, Art. no. 024610, 2021, doi: 10.1103/PhysRevFluids.6.024610.

[7] X. Liu, L. Chen, Y. Zhang, H. Tan, Y. Liu, and D. Peng, “Spanwise unsteadiness in the sidewall-confined shock-wave/boundary-layer interaction,” Journal of Fluid Mechanics, vol. 987, Art. no. R6, 2024, doi: 10.1017/jfm.2024.356.

[8] V. Pasquariello, S. Hickel, and N. A. Adams, “Unsteady effects of strong shock-wave/boundary-layer interaction at high Reynolds number,” Journal of Fluid Mechanics, vol. 823, pp. 617–657, 2017, doi: 10.1017/jfm.2017.308.

[9] M. C. Adler and D. V. Gaitonde, “Dynamic linear response of a shock/turbulent-boundary-layer interaction using constrained perturbations,” Journal of Fluid Mechanics, vol. 840, pp. 291–341, 2018, doi: 10.1017/jfm.2018.70.

[10] D. J. Lusher, S. P. Jammy, and N. D. Sandham, “Shock-wave/boundary-layer interactions in the automatic source-code generation framework OpenSBLI,” Computers & Fluids, vol. 173, pp. 17–21, 2018, doi: 10.1016/j.compfluid.2018.03.081.

[11] V. R. Petha Sethuraman, Y. Yang, and J. G. Kim, “Interaction of shock train with cavity shear layer in a scramjet isolator,” Physics of Fluids, vol. 35, no. 3, Art. no. 036111, 2023, doi: 10.1063/5.0137481.

[12] K. Sabnis and H. Babinsky, “A review of three-dimensional shock wave-boundary-layer interactions,” Progress in Aerospace Sciences, vol. 143, Art. no. 100953, 2023, doi: 10.1016/j.paerosci.2023.100953.

[13] F.-Y. Zuo and A. Memmolo, “Investigation of conical shock wave/boundary layer interaction in axisymmetric internal flow,” Aerospace Science and Technology, vol. 106, Art. no. 106106, 2020, doi: 10.1016/j.ast.2020.106106.

[14] N. Khobragade and R. Kumar, “Control of shock wave/boundary layer interactions in a supersonic air intake using a modified backward-facing step,” Shock Waves, vol. 32, pp. 467–481, 2022, doi: 10.1007/s00193-022-01091-5.

[15] X. Xin, Z. Wang, C. Lv, and J. Chang, “Mechanism of shock-train/boundary-layer interaction in spanwise concave isolator channels,” Acta Astronautica, vol. 199, pp. 232–248, 2022, doi: 10.1016/j.actaastro.2022.07.057.

[16] H. X. Huang, H. J. Tan, F. B. Li, X. B. Tang, W. Huang, L. Yan, and Z. B. Du, “Control mechanism of micro vortex generator and secondary recirculation jet combination in the shock wave/boundary layer interaction,” Acta Astronautica, vol. 200, pp. 56–76, 2022, doi: 10.1016/j.actaastro.2022.07.025.

[17] Z. B. Du, C. B. Shen, W. Huang, Y. Shen, and H. Wu, “Investigation on the three-dimensional shock wave/turbulence boundary layer control induced by the secondary recirculation jets,” Computers & Fluids, vol. 237, Art. no. 105341, 2022, doi: 10.1016/j.compfluid.2022.105341.

[18] X. Y. Zhong, W. Huang, L. Yan, H. Wu, and Z. B. Du, “Investigation on the adaptive control of shock wave/turbulent boundary layer interaction based on the secondary circulation jets,” Acta Astronautica, vol. 198, pp. 233–250, 2022, doi: 10.1016/j.actaastro.2022.06.016.

[19] K. Zhu, F. Xie, G. Wang, Y. C. Hu, Y. G. Yang, M. B. Sun, and W. D. Liu, “Separation characteristics of shock wave/turbulent boundary layer interaction under the effect of a transverse jet,” Physics of Fluids, vol. 35, no. 5, Art. no. 055142, 2023, doi: 10.1063/5.0148359.

[20] R. Quadros and M. Bernardini, “Numerical investigation of transitional shock-wave/boundary-layer interaction in supersonic regime,” AIAA Journal, vol. 56, no. 7, pp. 2712–2724, 2018, doi: 10.2514/1.J056650.

[21] N. Mahalingesh, S. Piponniau, and P. Dupont, “A universal scaling for the length scales of shock-induced separation,” Journal of Fluid Mechanics, vol. 1000, Art. no. A5, 2024, doi: 10.1017/jfm.2024.864.

[22] R. Mangalagiri and S. P. Jammy, “Sidewall effects in laminar ramp induced shockwave boundary layer interactions,” Computers & Fluids, vol. 267, Art. no. 106063, 2023, doi: 10.1016/j.compfluid.2023.106063.

[23] S. Priebe, J. H. Tu, C. W. Rowley, and M. P. Martín, "Low-frequency dynamics in a shock-induced separated flow," Journal of Fluid Mechanics, vol. 807, pp. 441–477, 2016, doi: 10.1017/jfm.2016.557.

[24] R. H. M. Giepman, R. Louman, F. F. J. Schrijer, and B. W. van Oudheusden, "Experimental study into the effects of forced transition on a shock-wave/boundary-layer interaction," AIAA Journal, vol. 54, no. 4, pp. 1313–1325, 2016, doi: 10.2514/1.J054501.

[25] H. X. Huang, H. J. Tan, S. Sun, Y. C. Zhang, and L. Cheng, "Transient interaction between plasma jet and supersonic compression ramp flow," Physics of Fluids, vol. 30, no. 4, Art. no. 041703, 2018, doi: 10.1063/1.5028493.

[26] W. Li and H. Liu, "Large-eddy simulation of shock-wave/boundary-layer interaction control using a backward facing step," Aerospace Science and Technology, vol. 84, pp. 1011–1019, 2019, doi: 10.1016/j.ast.2018.11.005.

[27] Y. T. Hong, Z. F. Li, and J. M. Yang, "Scaling of interaction lengths for hypersonic shock wave/turbulent boundary layer interactions," Chinese Journal of Aeronautics, vol. 34, no. 5, pp. 504–509, 2021, doi: 10.1016/j.cja.2020.12.028.

[28] C. S. Combs, J. D. Schmisseur, B. F. Bathel, and S. B. Jones, "Unsteady analysis of shock-wave/boundary-layer interaction experiments at Mach 4.2," AIAA Journal, vol. 57, no. 11, pp. 4715–4724, 2019, doi: 10.2514/1.J058073.

[29] K. Zhu, W. D. Liu, and M. B. Sun, "Impacts of periodic disturbances on shock wave/turbulent boundary layer interaction," Acta Astronautica, vol. 182, pp. 230–239, 2021, doi: 10.1016/j.actaastro.2021.02.017.

[30] M. C. Adler and D. V. Gaitonde, "Flow similarity in strong swept-shock/turbulent-boundary-layer interactions," AIAA Journal, vol. 57, no. 4, pp. 1579–1593, 2019, doi: 10.2514/1.J057534.

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