# -36-34 199511908 438// A CONTROLLED VARIATION SCHEME FOR CONVECTION P. 20 TREATMENT IN PRESSURE DAMAGE IN CONVECTION P. 20 TREATMENT IN PRESSURE-BASED ALGORITHM

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Convection effect and source terms are two primary sources of difficulties in computing turbulent reacting flows typically encountered in propulsion devices. The present work intends to elucidate the individual as well as the collective roles of convection and source terms in the fluid flow equations, and to devise appropriate treatments and implementations to improve our current capability of predicting such flows. A controlled variation scheme (CVS) has been under development in the context of a pressure-based algorithm, which has the characteristics of adaptively regulating the amount of numerical diffusivity, relative to central difference scheme, according to the variation in local flow field. Both the basic concepts and a pragmatic assessment will be presented to highlight the status of this work.



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# A CONTROLLED VARIATION SCHEME FOR CONVECTION TERM TREATMENT IN PRESSURE-BASED ALGORITHM

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<ul> <li>Handle Different Physics &amp; Varying Number of Unknowns: u, v, w, p, e, T, k, etc. Without Reformulating the Algorithm</li> <li>Suitable for Incompressible &amp; Compressible Flows</li> <li>Suitable for Steady &amp; Unsteady <i>Flows at All Speeds</i></li> <li>Modern Concepts, e.g., Modern Discretization Schemes, Multigrid, Composite Grids, etc. Should be Implementable, in Principle</li> <li>Pressure-Based Sequential Solver</li> </ul>	
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	Treatment of Convection
	<ul> <li>Convection terms: Strong Nonlinearity</li> </ul>
	<ul> <li>Critical Situations</li> <li>High Local Cell Peclet Numbers (Convection Dominates Diffusion)</li> <li>Sharp Gradients in Flowfield</li> <li>Recirculation</li> <li>Interaction of Convection with Turbulence, Chemical Reactions, etc.</li> <li>Presence of Source Terms</li> </ul>
1892	<ul> <li>Flows with Sharp Gradients, e.g., Shocks</li> <li>Any First-Order Scheme → too diffusive</li> <li>Any Linear Second-Order Scheme → spurious oscillations near sharp gradients</li> <li>Remedy → Nonlinear Second-Order TVD (Total Variation Diminishing) Schemes</li> </ul>
	<ul> <li>Source Terms: Cause Numerical Difficulties Due to Different Length an Time Scales</li> </ul>

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Present Approach	quential Solver	plicit Control of Numerical Viscosity Based on Total Variation Diminshing (TVD) Concept Controlled Variation Scheme (CVS)	ses Studied	Compressible Shock Tube Flows Longitudinal Combustion Instability Incompressible Recirculating Flows (Laminar and Turbulent)
	Sequen	<ul> <li>Explicit</li> <li>Base</li> <li>Con</li> </ul>	Cases S	► Com Long

Scheme
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Scalar Conservation Law

$$\frac{\partial w}{\partial t} + \frac{\partial f(w)}{\partial x} = 0$$

Implicit TVD Scheme

$$w_i^{n+1} + \left( \tilde{f}_{i+1/2}^{n+1} - \tilde{f}_{i-1/2}^{n+1} \right) = w_i^n$$

Numerical Flux

$$\tilde{f}_{i+1/2}^{n+1} = \frac{1}{2} \begin{bmatrix} f_i + f_{i+1} + g_i + g_{i+1} - Q(a_{i+1/2} + \gamma_{i+1/2}) \Delta_{i+1/2}w \\ \text{Central Diff. Anti-diffusion Numerical Dissipation Flux Flux Flux  $F$$$

Linear Steady Burgers' Equation

$$\alpha \phi_x = \beta \phi_{xx}$$
  $\alpha, \beta = constants > 0$   
 $\phi(0) = 0$ ,  $\phi(1) = 1$ 

• Cell Peclet Number (P)

$$P = \frac{\alpha}{\left[\frac{\beta}{h}\right]} = local \left[\frac{convection}{diffusion}\right]$$

Central Difference Scheme

$$(2 - P) \phi_{i+1} - 4\phi_i + (2 + P) \phi_{i-1} = 0$$

Critical Value : | P | > 2

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Ratio of Local Convection to Diffusion Strength

Diffusion (CVS) = Physical + Numerical

$$P_{cvs} = \frac{\alpha}{\left[\frac{\beta}{h} + \alpha \left\{\frac{\overline{Q}_{i+1/2} - \overline{G}_{i+1/2}}{\Delta_{i+1/2}\phi}\right\}\right]}$$

Normalized Viscosity







Model Problem II: Different Schemes



Model Problem II: Dirichlet B.C., P=100 Effective Cell Peclet Number

i	x	P <sub>cvs</sub>
2	0.42	1.96
9	3.42	1.96
10	3.85	3.15
11	4.28	4.66
12	4.71	6.32
13	5.14	24.85
34	14.14	1.97
35	14.57	1.96
Remaining i	Remaining x	100.00

# **Treatment of Source Terms**

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Using TVD Type Sequential Solver

MacCormack's Predictor-Corrector Strang's Operator–Splitting Special Techniques :

1-D Longitudinal Combustion Instability Problem

### TREATMENT OF SOURCE TERMS: A LONGITUDINAL COMBUSTION INSTABILITY PROBLEM

Besides convection terms, source terms (if present) in the Navier–Stokes equations can be strong enough to cause numerical difficulties such as a loss of accuracy in the form of spurious oscillations in the solution profiles or numerical instability. This is so because strong source terms can be sufficiently stiff and the time and length scales imposed by them may not be commensurate with those imposed by convection, for example. Thus, due attention has to be paid to the source terms and not just to the convection terms.

A one-dimensional longitudinal combustion instability problem is chosen which has a strong heat release source term. The high accuracy TVD type of convection treatment in a sequential solver (second fig. clockwise: top right) is seen to provide higher accuracy than the first-order upwind scheme (first figure: top left), as evident from the amplitudes of the ten pressure modeshapes shown in the viewgraph. However, the TVD type of convection treatment without any special source term treatment yields spurious oscillations in modehapes numbered 5, 6 and 7 (second figure clockwise). From the corresponding heat release modeshapes (third fig. clockwise), it is clear that modes 5, 6 and 7 are the modes of maximum heat release, thus demonstrating that when source terms become stiff enough they may lead to spurious oscillations. This can be resolved by increasing the amount of numerical dissipation in the scheme (by varying  $\delta$ ) but this is accompanied by an overall smearing of solution profiles. However, special source term treatment such as MacCormack's predictor-corrector method or Strang's time-splitting method (here, the latter) can resolve the problem by suppressing any spurious oscillations without the need of any extra numerical damping. This is clearly evident from the bottom left plot (fourth fig. clockwise).

### Special Source Term Treatment

Conservation law with a source term

 $w_t + f(w)_x = \psi(w)$ 

### Treatment

a) MacCormack's Predictor-Corrector Method

b) Operator Splitting (Strang's Time-Splitting)

$$W^{n+1} = S_{\psi}(\Delta t/2) S_f(\Delta t) S_{\psi}(\Delta t/2) W^n$$

where  $S_f$  represents the numerical solution operator for

$$w_t + f(w)_x = 0$$

and  $S_{\psi}$  is the numerical solution operator for the ODE

$$w_t = \psi(w)$$

### **1–D** Combusting Flow in a Duct

- To illustrate the effect of a strong source term (heat release) on numerical accurcay
- To demonstrate the efficacy of special source term treatment for a strong source term



### **Combustion Instability Problem : Mode Shapes**



 $\delta = 0$ 



Normalized Viscosity (Q\* - G\*)



## Streamfunction: Backward-Step, Turbulent Flow Re = 132,000

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Q\*-G\* on Various Grids

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